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APPLICATION OF ARTIFICIAL INTELLIGENCE TECHNIQUES TO EXTERIOR BALLISTICS

MARK FISCHER
ROBERT WHYTE
NICK STRAGUZZI

DECEMBER 1989

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U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) BRL-CR-622	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION General Electric 6b. OFFICE SYMBOL *(If applicable)*	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS *(City, State, and ZIP Code)* Armament Systems Department Burlington, VT 05401-4985	7b. ADDRESS *(City, State, and ZIP Code)*
8a. NAME OF FUNDING/SPONSORING ORGANIZATION U.S. Army Ballistic Research Laboratory 8b. OFFICE SYMBOL *(If applicable)* SLCBR-LF	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER Contract No. DAAA15-88-C-0006
8c. ADDRESS *(City, State, and ZIP Code)* Aberdeen Proving Ground, MD 21005-5066	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

11. TITLE *(Include Security Classification)*

Application of Artificial Intelligence Techniques to Exterior Ballistics (U)

12. PERSONAL AUTHOR(S)

Mark Fischer, Robert Whyte, and Nicholas Straguzzi

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT *(Year, Month, Day)*	15. PAGE COUNT
Contract Report	FROM 02/88 TO 05/89		68

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
FIELD	GROUP	SUB-GROUP	Exterior Ballistics
19	10		Trajectory
19	06		Aeroballistics

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

This report documents the application of Artificial Intelligence to the problem of predicting the aerodynamic stability boundaries of spin stabilized projectiles. This work was accomplished by the Armament Systems Department of General Electric under U.S. Government Contract DAAA15-88-C-0006 during the period from February 1988 to May 1989.

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20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL William P. D'Amico	22b. TELEPHONE *(Include Area Code)* (301)-278-3405 22c. OFFICE SYMBOL SLCBR-LF-A

DD Form 1473, JUN 86 *Previous editions are obsolete.*

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

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I. Introduction

This is the final report of the work accomplished on contract DAAA15-88-C-0006, Application of Artificial Intelligence(AI) Techniques to Exterior Ballistics. This report covers the period from February 1988 thru May 1989. The sponsor was the U.S. Army Ballistic Research Laboratory (BRL), Aberdeen Proving Ground.

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II. Objective

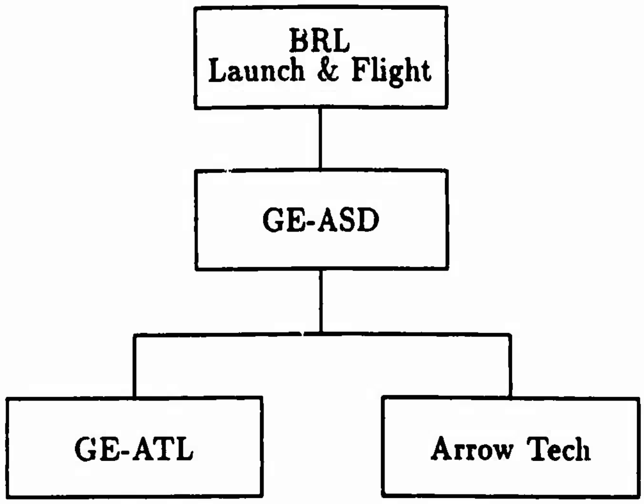
The application of Artificial Intelligence (AI) to the analysis of the free flight characteristics(static and dynamic stability) of projectiles and provide a method of recommending corrections (alterations) to the geometry and physical properties to improve flight performance (as required) are the end item goals of this project. To accomplish these goals the analyst must be provided with a set of tools/data with acceptable reliability including:

- Aerodynamic Coefficients(Predictions or Test Data);
- Stability Analysis Methodology;
- Trajectory Simulation(~~6DOF~~,2DOF)
- Physical Modeling(~~Weight~~,CG,Inertias,etc.)
- AI Expert System. Keywords: Exterior ballistics, Trajectories, Aeroballistics. (SDW)

Portions of all required tools (except AI) were contained within the GE PRODAS code. Deficient areas were Aerodynamic Coefficients (prediction accuracy), Stability Analysis Methodology, and the lack of an Expert System to assist the user in analyzing this complex problem.

The mitigation of these deficient areas was been divided among the program team members. The contractor team is comprised of the GE Armament Systems Department (GE/ASD), the GE Advanced Technology Laboratories (GE/ATL), and Arrow Tech. These responsibilities are outlined below. Figure 1 illustrates the relationship of the project team.

- GE/ASD — System Integration(PRODAS+Aero Data Bank+AI)
- GE/ATL — Artificial Intelligence Software and expert interviews
- Arrow Tech — Aero Data Bank and Stability Methodology
- BRL — Provide Aero Test Data and Critique Program



Team Member	Tasks	Technical Contact
BRL	Sponsor / Experts	Bill D'Amico
GE-ASD	PRODAS / System Interface	Mark Fischer
GE-ATL	AI - Expert System	Nick Straguzzi
Arrow Tech	Data Bank - Stability Methods	Bob Whyte

Figure 1. AI - Exterior Ballistics Program Team

III. Discussion

1. Background

The PRODAS computer program was selected as a baseline for developing AI assisted aeroballistic analysis. Documentation of PRODAS is covered in References 1, 2, and 3. PRODAS development began at the Armament Systems Dept. of General Electric as a internally funded project in 1972. During subsequent years, new capabilities were added and existing capabilities were continuously improved. PRODAS now contains over 50000 lines of Fortran code. Graphical presentations utilize Tektronix PLOT-10 routines.

A functional diagram of the various PRODAS segments is shown in Figure 2. Those segments which were altered substantially in order to provide the proper interface with the new AI segments are shown with double borders. The interface and operational flow of the AI segments are shown in Figure 3.

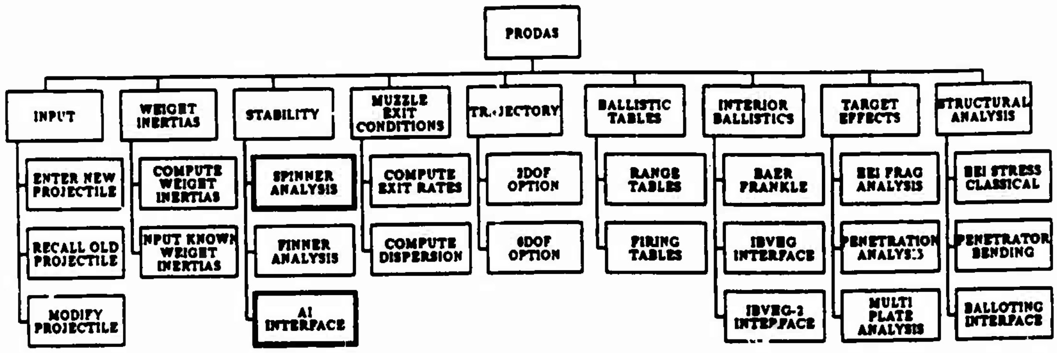


Figure 2. PRODAS - Projectile Design and Analysis System

The major exterior ballistic segments of PRODAS are described below.

- SPINNER (Ref. 4) The SPINNER code was developed for Picatinny in 1973 to facilitate estimating the aerodynamic coefficients of spin stabilized projectiles. The only inputs required are the key geometric dimensions of the projectile (ie Total Length, Nose Length, etc.).
- FINNER (Ref. 5) The FINNER code was developed to allow rapid prediction of the aerodynamics of fin stabilized projectiles. Inputs required, like SPINNER, are the key geometric features of the projectile.
- MUZZLE EXIT (Ref. 6) This code predicts the "aerodynamic jump of projectile due to in-bore clearence. Initial angular rate and first maximum yaw are also computed.
- TRAJECTORY (Ref. 7) This segment contains both a 2DOF with drift and a full 6DOF trajectory program. Many options exist including winds, tracers, rockets, firing from moving platforms, firing from rotating gun barrels, ball rotor fuze moving parts, etc.
- BALLISTIC TABLES (Ref. 8) This segment consists of several firing table format output options for use in setting up live firing tests or for use in deriving fire control equations. A very large matrix of trajectories are automatically executed after the simple interactive inputs are complete.

Reference 1 descibes in detail the technical background of the various program segments including Interior Ballistics, Structural, and Target Effects. Many additional references are cited in the Technical Manual.

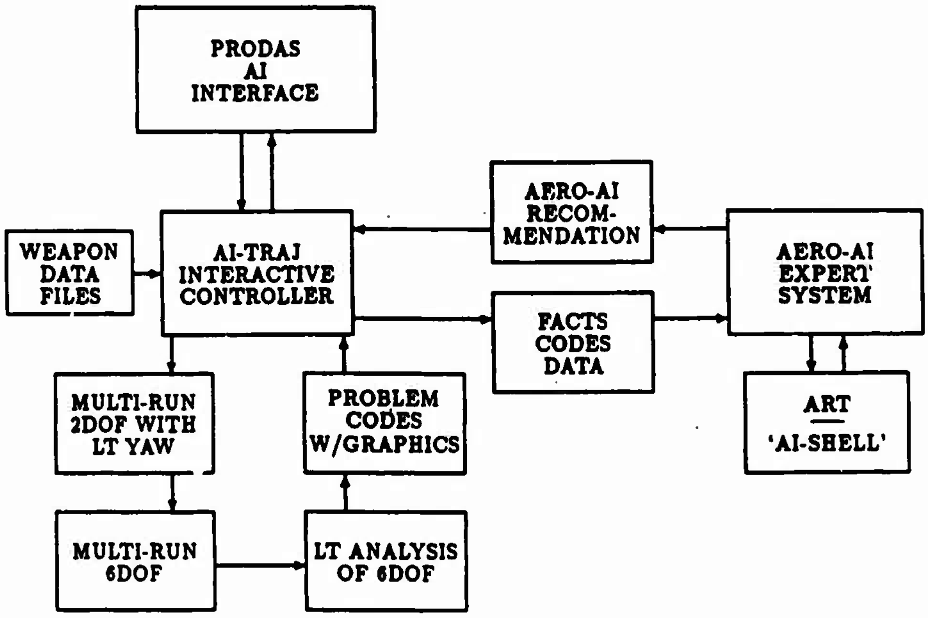


Figure 3. AI - PRODAS Data Flow

2. Status of Revisions

The status and features of the newly developed codes are briefly listed in this section. Each area will be discussed in greater depth in the same order in following subsections.

- An experimental Aerodynamic Data Bank was established for 'Spinners'.
- SPINNER Code Updates were made:
  1. added Mach No's 6, 8, and 10
  2. added Magnus moment prediction to 10 degrees yaw
  3. added Magnus moment prediction for Boomed Projectiles
  4. revised stability output
- An automatic 2/6DOF Trajectory Program (AI-TRAJ) was developed with the following features:
  1. Data bank of projectile/gun combinations
  2. Non-linear Magnus monent by Table Lookup rather than polynominal expansion
  3. Simulated stable and unstable flights utilizing Linear Theory in combination with 2DOF trajectory simulation
  4. Identified unstable situations and automatically initiated 6DOF simulations for confirmation
  5. Created file to be read by the Artificial Intelligence code AERO-AI

- Baseline PRODAS modifications:
  1. Interface with AI-TRAJ and AERO-AI
  2. File structure changed to be compatible with improved non-linear Magnus model
- AI stability rules developed and coded based on interviews with R. Whyte of Arrow Tech and R. McCoy of BRL.
- AERO-AI system developed at GE/ATL
- AI-PRODAS trials at Arrow Tech
- AI-PRODAS installation at BRL

3. Aerodynamic Data Bank

The SPINNER (Ref. 2) code contained within PRODAS had not been modified since 1973 except for an update to the computation of the spin decay coefficient in 1979. The program was developed by fitting equations to available experimental 'data'. This 'data' base had been saved at GE/ASD and was reviewed for accuracy and adequacy. New data acquired since 1973 was added to the data base which brought the total spin stabilized data base to over 100 projectiles of all calibers and shapes. To assure that only the most important and accurate data be utilized for predicting the coefficients of projectiles under study, only the 'best' 50+ sets of data (AEROS) were retained for use by AI-PRODAS. Figure 4 presents the descriptor and caliber for the projectiles contained in the data base. The data base was further refined by adding Magnus moment data at two and five degrees of yaw where available. The 155mm XM483 projectile will be used for illustrative purposes in this report. The exterior projectile shape is shown in Figure 5.

An example of the data base format for this XM483 projectile in shown in Figure 6. This data base may be altered or added to as described in Reference 3. Appendix A presents, for the XM483, a minimal set of typical printed/plotted output available to the user during an analysis session prior to entering the AI segment.

4. Aerodynamic Coefficients and Predicted Errors

The prediction of aerodynamic coefficients and their errors was a major goal of this project with the top goal of this project being prediction/computation and understanding of the expected flight performance of spin stabilized projectiles. This requires that not only must the drag coefficient be known but that excellent estimates of the normal force, pitching moment, damping moment, spin decay moment, and Magnus moment must be available as functions of Mach number and angle of attack (non-linearities).

To accomplish the estimate process the following steps are accomplished utilizing user friendly prompts incorporated in PRODAS. During the contract this process was refined and user friendly aspects improved.

Round Designation	Round Number	Author	Round Designation	Round Number	Author
5CALF	BRL MR876	MURPHY	5CALM	BRL MR876	MURPHY
5CAL	BRL MR876	MURPHY	7CALF	BRL MR876	MURPHY
7CALM	BRL MR876	MURPHY	7CALR	BRL MR876	MURPHY
7CALBAND	BRL MR876	MURPHY	7CAL	BRL MR1302	SCOTT
7CAL	BRL MR1302	SCOTT	9CALF	BRL MR876	MURPHY
9CALM	BRL MR876	MURPHY	9CALR	BRL MR876	MURPHY
CONECYLR	BRL MR1258	BOYER	CONECYLF	BRL MR1258	BOYER
PGU-28	AFTR-8696	GATES	IMP 20MM	AEDCTR7028	WATT
MK149	GEDB	GE	M56	GEDB	GEASD
M793	AFTR8227	WHYTE	M791	GEDB	GE
PGU14BHI	GEDB	GE			
PGU15BHI	GEDB	GE			
PGU13BHI	GEDB	GE			
XM788	BRLMR3019	MCCOY			
M789	BRL2432	MCCOY			
WC30	PA TR3422	WHYTE			
M1	BRL MR929	ROECKER			
XM380E5	BRL MR2023	KRIAL			
5/54	BRL MR2017	DONAVAN			
M101F	BRL MR1582	KARPOV			
M101R	BRL MR1582	KARPOV			
M483A1	PA CR 79016	WHYTE			
M549	PA CR80023	WHYTE			
XM454	BRL MR1369	SCOTT			
P1					
BRL SARP2	BRL MR1630	BRAUN			
BRL M97	BRL MR1630	BRAUN			
T5047E1					
T203	BRL MR956	KARPOV			
SRI-175					
HS831	BRL MR2466	NIETZEL			
M788	BRL2432	MCCOY			
T306	BRL MR1908	ROECKER			
M71	BRL MR1475	BOYER			
XM380E6	BRL MR2023	KRIAL			
5/38	BRL MR2071	DONAVAN			
XM617	BRL MR1998	BRANDON			
M101	BRL MR1582	KARPOV			
XM483	PA TR 4872	CRAVER			
XM795	PA CR 79016	WHYTE			
M454	BRLMR1369	SCOTT			
BRL	BRLMR824	SCHMIDT			
BRL P1	BRL MR1630	BRAUN			
BRL T216E1	BRL MR1630	BRAUN			
BRL 223	BRL MR1630	BRAUN			
M437	PATR1646	WHYTE			

Figure 4. Data Base Contents - Spin Stabilized Projectiles

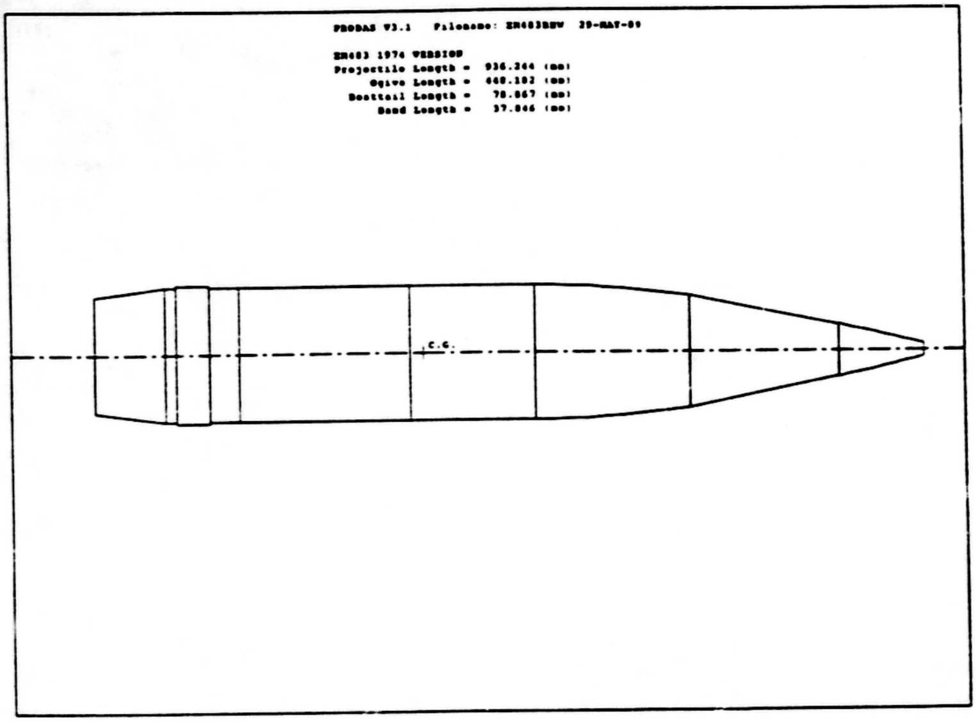


Figure 5. XM483 - PRODAS Model Exterior Shape

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XM483
PA TR 4872
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CRAVER

0.60500E+01	0.28400E+01	0.51000E+00	0.36600E+01	0.98000E-01
0.10180E+01	0.25000E+00	0.52000E+01	1.53000E+01	0.10000E+01
0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0.70000E+01
6.092	102.	510.	6100.	2800.
700.	1.0	10.0		

0.1320	0.1320	0.1320	0.1580	0.2200	0.3305	0.3650	0.3650	0.3580	0.3480
0.3290	0.3040	0.2790	0.2450	0.0000	0.0000	0.0000			
1.8000	1.8000	1.8000	2.0000	2.1000	2.1000	2.1000	2.1500	2.3000	2.4000
2.5000	2.6250	2.7500	2.8500	0.0000	0.0000	0.0000			
4.7500	4.7500	5.0000	5.4000	5.4000	5.2000	5.0500	4.9500	4.8500	4.7600
4.7300	4.7000	4.6500	4.6000	0.0000	0.0000	0.0000			
-10.	-10.	-10.	-16.	-22.	-23.	-25.	-27.	-29.	-29.
-29.	-29.	-29.	-29.00	0.0000	0.0000	0.0000			
-.4	-.4	-.6	-.2	1.0	0.7	0.75	0.8	0.8	0.8
0.8	0.8	0.8	0.8	0.0000	0.0000	0.0000			
0.05	0.05	-0.2	1.0	1.9	1.0	0.95	0.9	0.85	0.8
0.8	0.8	0.8	0.8	0.0000	0.0000	0.0000			
0.9	0.9	1.1	2.0	2.5	1.25	1.15	1.05	0.95	0.9
0.85	0.8	0.8	0.8	0.0000	0.0000	0.0000			
-.03	-.03	-.03	-.03	-.028	0.0	0.0	0.0	0.0	0.0
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000			

Figure 6. Data Base Format Example - XM483

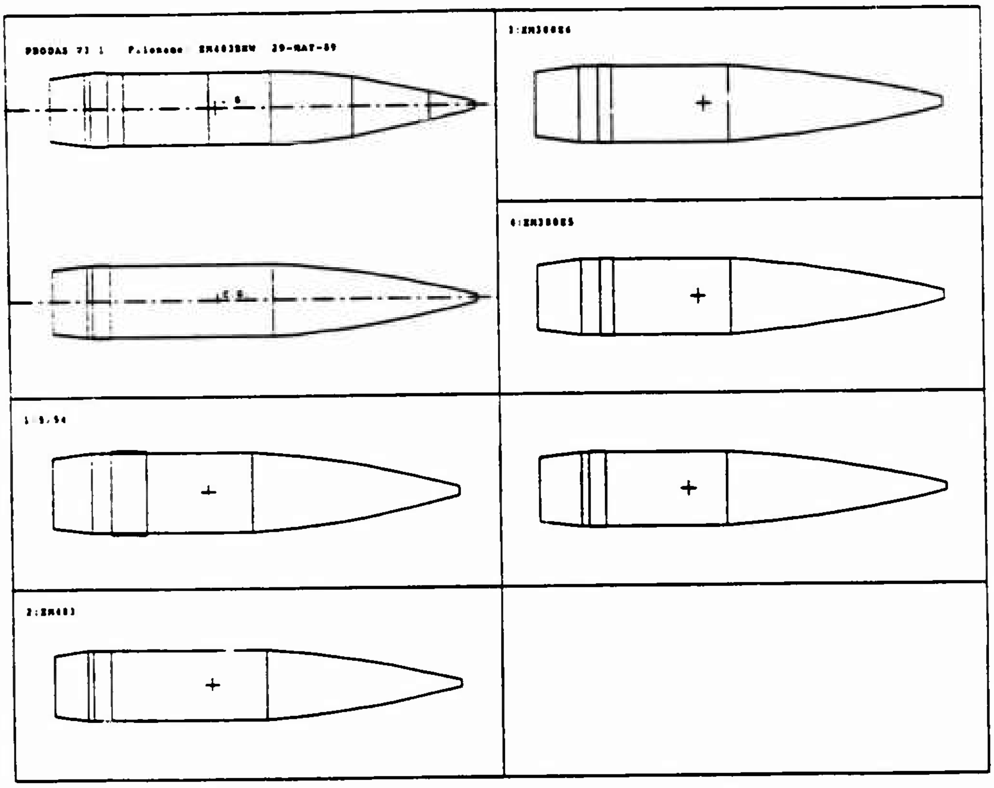


Figure 7. Similiar Projectile Shapes - XM483

Select which projectiles to include in the computation of the probable error.
Include flag is at the end on each entry
1 for Include flag mean projectile is used
0 for Include flag mean projectile is not used

Round Designation	Total Length	Ogive Length	Boat Tail Length	CG from Nose	Ogive Radius	Meplat Diameter	Boom Length	Diameter (mm)	
1 - 5/54	5.26	2.63	0.52	3.21	13.0	0.11	0.00	126.62	- 1
2 - XM483	6.05	2.84	0.51	3.66	15.3	0.10	0.00	154.74	- 1
	6.05	2.85	0.51	3.66	15.3	0.10	0.00	154.69	
3 - XM380E6	5.58	2.90	0.59	3.24	18.6	0.13	0.00	104.83	- 1
4 - XM380E5	5.58	2.90	0.59	3.34	18.6	0.13	0.00	104.83	- 1
5 - M549	5.64	3.01	0.58	3.53	18.9	0.10	0.00	154.74	- 1

Figure 8. Geometric Parameters Similiar Projectiles - XM483

Figure 7 shows the outline of the XM483 and also the outlines of the 5 similiar projectiles contained in the AEROS data base. The user is also shown a list of the key physical attributes of the similiar projectiles (Figure 8) and is allowed to choose which of these projectiles are to be used in the computation of the aerodynamic coefficients.The projectiles are listed in order of increasing nose length with the subject projectile listed between the dotted lines.

When selecting projectiles for inclusion in the Figure 8 list, the program uses the following rules (criteria).

- Total Length - The total length must be within 0.7 calibers of the subject projectile.
- Boattail - If the subject projectile has a boattail length greater than 0.65 calibers, all projectiles with boattails greater than 0.45 calibers are considered. If the boattail is between 0.3 and 0.65 calibers long, all projectiles with boattail lengths between 0.3 and 0.65 calibers are considered. For shorter boattails, all projectiles with boattail lengths up to 0.5 calibers are considered.
- Nose Length - Initially the nose length must be within 0.2 calibers. If the program selects fewer than 6 projectiles from the library, nose lengths up to a delta of 0.3 calibers will be included. If fewer than 6 projectiles still have not been selected, differences of 0.4 will be used. The program will not go beyond a 0.4 caliber differential.

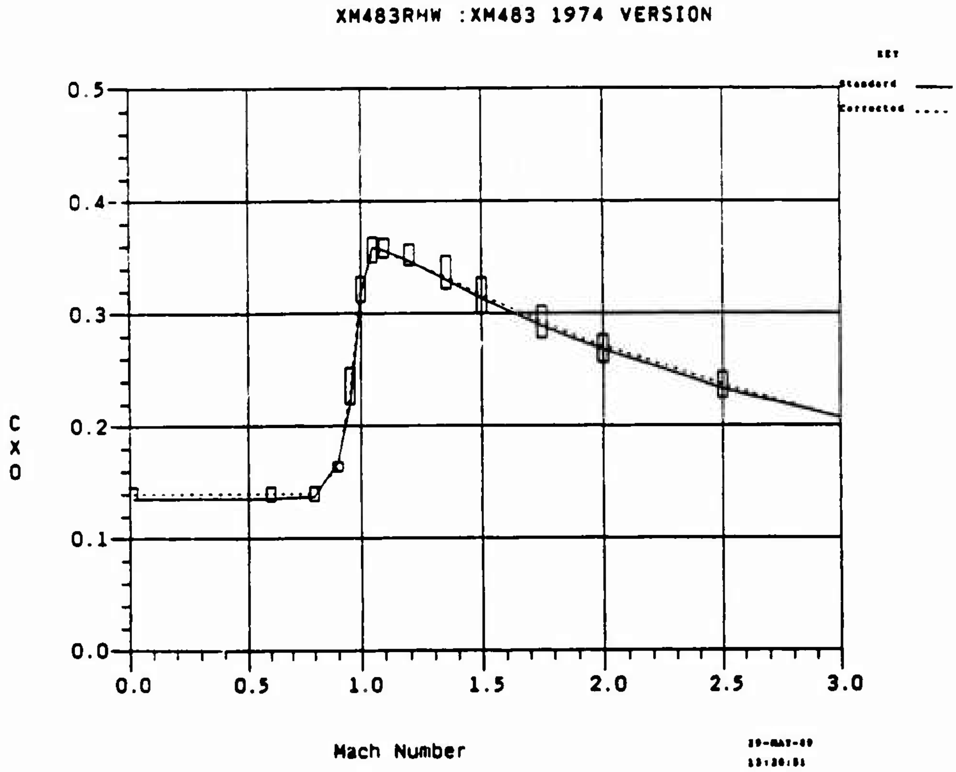
At this point the program, in turn, computes the aero's using SPINNER for each similiar projectile and determines the difference between the SPINNER prediction and the AEROS file. The mean error of all similiar projectiles is computed for each coefficient and Mach number. These mean errors are then added to the SPINNER prediction of the projectile under analysis to produce a 'best' estimate of the aerodynamic coefficients. The coefficients are displayed in graphical form along with their error bound (Figure 9). The error bound represents the maximum plus and minus error determined for each similiar projectile at each Mach number containing data. A tabulated sample for the XM483 is shown in Figure 10.

The user is also provided the opportunity to adjust the coefficients through table editing or by altering the data using the screen cursor to change the shape of the displayed curve (i.e. 'Mouse'). In this manner actual test data can be input to replace computed values.

5. Stability Methodology - AI-TRAJ Implementation

Assuming the aerodynamic coefficients have been defined by either test data or by the method described above, the analysis/prediction of the performance of projectiles still remains a complex problem involving many variables. Some of these are listed below.

- Application (Artillery,Tank/IFV, Anti-Aircraft, or Aircraft Mounted)
- Muzzle Velocity (several zones from subsonic to supersonic)
- Quadrant Elevation (high angle trailing)
- Weapon/Gun (different rifling/twist)
- Atmosphere (cold, ambient, and hot)
- Muzzle Tipoff (Worn guns, variable angular rates)
- Winds
- Side/Forward firing from moving platform



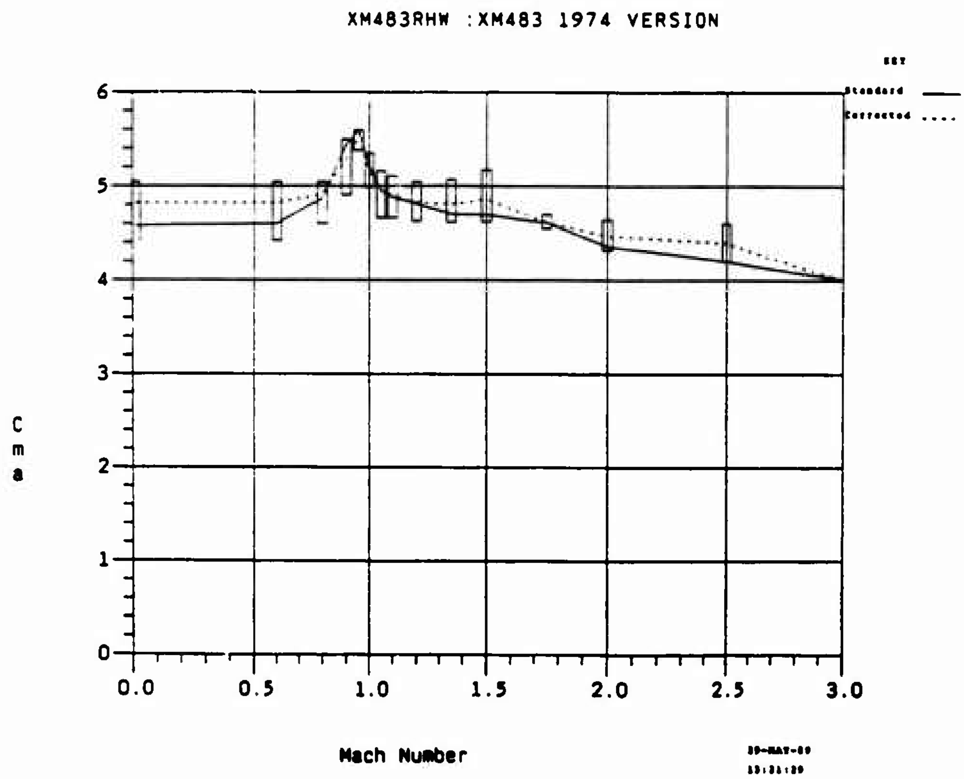


Figure 9. Aerodynamic Coefficients - Error Bounds

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Stability Results

	Projectile Length	Ogive Length	Boattail Length	Boom Length	C.G. from Nose	Band Diameter	Meplat Diameter	Ogive Radius	Rifling Twist
in mm	936.244	440.182	78.867	0.000	566.151	157.988	15.240	2366.696	3101.340/rev
in calibers	6.053	2.846	0.510	0.000	3.660	1.021	0.099	15.300	20.000/rev

Diameter (mm)	Weight (kg)	Gun Bore (mm)	Temperature (Deg C)	Air Density (gm/cm**3)	Axial Mom. (kg-cm**2)	Trans. Mom. (kg-cm**2)
154.686	46.266	155.067	15.000	0.001225	1492.46399	17851.03906

Aerodynamic Coefficients

Spinner Prediction

Mach	CX	CX2	CNa	Cma	CPN	CYpa	Cnpa-0	Cnpa-2	Cnpa-5	Cnpa-10	Cnpa3	Cnpa5	Cmq	Clp
0.010	0.133	2.689	1.800	4.755	1.018	-1.019	-0.397	0.053	0.903	1.03	170.77	-4035.	-10.1	-0.031
0.600	0.133	2.689	1.800	4.755	1.018	-1.019	-0.397	0.053	0.903	1.03	170.77	-4035.	-10.1	-0.031
0.800	0.133	3.182	1.800	5.005	0.879	-1.019	-0.597	-0.197	1.103	1.12	154.86	-3618.	-10.1	-0.031
0.900	0.160	3.703	2.000	5.407	0.956	-1.140	-0.197	1.003	2.003	1.42	109.78	-2191.	-16.1	-0.031
0.950	0.222	4.214	2.100	5.400	1.088	-1.443	1.004	1.904	2.504	1.83	82.34	-1200.	-22.1	-0.029
1.000	0.333	4.706	2.100	5.199	1.184	-1.322	0.704	1.004	1.254	1.26	59.17	-1187.	-23.1	-0.028
1.050	0.367	5.193	2.099	5.041	1.259	-1.201	0.754	0.954	1.154	1.02	36.53	-826.	-25.1	-0.028
1.100	0.367	5.766	2.149	4.941	1.361	-1.140	0.803	0.903	1.053	0.99	25.66	-548.	-27.1	-0.028
1.200	0.361	6.349	2.299	4.840	1.555	-1.019	0.803	0.853	0.953	0.93	18.03	-362.	-29.1	-0.028
1.350	0.351	5.783	2.399	4.750	1.680	-1.019	0.803	0.803	0.903	0.93	14.85	-278.	-29.1	-0.027
1.500	0.331	5.191	2.499	4.721	1.771	-1.019	0.803	0.803	0.853	0.94	13.26	-237.	-29.1	-0.027
1.750	0.306	4.616	2.624	4.692	1.872	-1.019	0.804	0.804	0.804	0.94	11.67	-195.	-29.1	-0.026
2.000	0.281	4.005	2.749	4.642	1.972	-1.019	0.804	0.804	0.804	0.95	10.08	-153.	-29.1	-0.026
2.500	0.247	3.308	2.850	4.595	2.048	-1.019	0.804	0.804	0.804	0.95	8.49	-111.	-29.1	-0.025
3.000	0.207	2.785	2.844	4.011	2.250	-1.019	0.799	0.838	0.847	0.94	6.89	-70.	-35.0	-0.025
4.000	0.169	2.312	2.744	3.952	2.220	-1.019	0.798	0.837	0.846	0.94	6.89	-70.	-34.9	-0.025
5.000	0.147	1.840	2.644	3.887	2.190	-1.019	0.795	0.834	0.844	0.94	6.89	-70.	-34.8	-0.024
6.000	0.131	1.647	2.594	3.866	2.170	-1.019	0.794	0.832	0.842	0.94	6.89	-70.	-34.7	-0.024
8.000	0.121	1.561	2.564	3.847	2.160	-1.019	0.793	0.831	0.841	0.94	6.89	-70.	-34.7	-0.023
10.000	0.114	1.467	2.544	3.842	2.150	-1.019	0.792	0.831	0.841	0.94	6.89	-70.	-34.6	-0.022

Figure 10. Tabulated Aerodynamic Coefficients - XM483

To assist the user in considering and implementing sufficient analysis, a special purpose trajectory code (AI-TRAJ) has been developed. The features of this code are outlined below for the artillery mission. The other applications were not implemented in the current contract although the program structure was designed to accomodate future additions.

- Initial Conditions (Total 384 maximum combinations)
  1. Muzzle Velocity: all zones from gun file are run (8 maximum)
  2. Gun Elevation : 15, 30, 45, and 65 degrees
  3. In-Bore Yaw : 1.0, 2.5, 4.0 and 6.0 mils
  4. Sea Level Temperature : 15, and -40, +45 deg-C
- 2DOF Simulations
  1. Linear Theory computations of fast and slow vectors during trajectory
  2. Drag includes computed yaw effects
  3. Drag form factor computed which is required to achieve desired range
  4. Short Range and stability problem categorized (initial diagnosis)
  5. Inputs set up for 6DOF confirmation trajectories
- 6DOF Simulations of selected cases
- Stability Analysis of 6DOF motion by Linear Theory (AIYAWLT)

2. Fit 6DOF motion (Theta,Psi) using least squares
3. Identify stable and unstable vectors
4. Compare 6DOF results with 2DOF results (final diagnosis)
5. Prepare Inputs (File AI-RCA for ATL's AERO-AI)

Appendix B steps through this process with a representative case (XM483). The outputs from AI-TRAJ are provided to the GE-ATL expert system as file (AI-RCA) for use by the expert system discussed in Section IV.

a. 2DOF Simulation with Yaw

The run time associated with executing a possible total of 384 6DOF trajectories is prohibitive unless a super computer is utilized. The super computer route was not chosen as it was judged to be a waste of a resource which could be better used for CFM, FEM, and other computationally intensive processes.

Instead, Linear Theory computations were imbeded into the 2DOF trajectory simulation with two goals in mind.

1. Compute Mean Yaw by Linear Theory thus allowing yaw drag simulation
2. Identify unacceptable slow or fast arm growth (undamping)

The following initial setups and conditions are computed based on the trajectory to be executed. All specified combinations of muzzle velocity, gun elevation, sea level temperature and in-bore yaw angle will be executed in turn.

- Muzzle Gyroscopic Stability Factor

$$S_g = \frac{2I_x^2p^2}{\pi\rho I_y C_{m\alpha} d^3 V^2}$$

- Ballistic Factor

$$\sigma = \sqrt{1. - \frac{1.}{S_g}}$$

- Fast / Slow Epicylic Rates

$$\dot{\phi}_F = (1+\sigma)\left(\frac{pI_x}{2I_y}\right)$$

$$\dot{\phi}_S = (1-\sigma)\left(\frac{pI_x}{2I_y}\right)$$

- Initial Angular Rate

$$\dot{\alpha} = p\alpha_g$$

- **First Maximum Yaw Angle**

$$\bar{\alpha}_{max} = \frac{p a_y}{(\frac{1}{2} V(\dot{\phi}_F - \dot{\phi}_S))}$$

- **Initial Fast / Slow Arm Magnitudes**

$$K_F = \frac{\bar{\alpha}_{max}}{2}$$

$$K_S = \frac{\bar{\alpha}_{max}}{2}$$

- **Define Numerical Integration Time Step (Empirical)**

$$\Delta t = 1.2(\frac{d}{V})$$

Example:

d mm	V m/s	Δt sec.	Calibers of Travel	Travel meters
30	500	0.072	1200	36
105	500	0.252	1200	126
200	500	0.480	1200	240

The sequence of events during the computation of a single time step of a 2DOF trajectory are listed below. Where appropriate, the key equations are stated.

1. Compute the mean yaw squared

$$\bar{\delta}^2 = K_{F_i}^2 + K_{S_i}^2$$

2. Compute the Aerodynamic Coefficients at the mean yaw

$$C_X = C_{X_o} + C_{X_2}\bar{\delta}^2$$

$$C_{N\alpha} = C_{N\alpha o} + C_{N\alpha 3}\bar{\delta}^2$$

$$C_{m\alpha} = C_{m\alpha o} + C_{m\alpha 3}\bar{\delta}^2$$

$$C_{mq} = C_{mqo} + C_{mq\alpha 2}\bar{\delta}^2$$

$$C_{np\alpha} = (\text{Table Lookup of } C_{np\alpha} \text{ versus } \bar{\delta}^2)$$

3. Compute the Yaw of Repose

$$K_R = \frac{I_x p g \cos\gamma}{\bar{q} A d V C_{m\alpha}}$$

4. Compute the accelerations to be integrated

$$\ddot{X} = f(C_X, C_{N\alpha}, K_R, \bar{\delta}^2)$$

$$\ddot{Y} = f(C_X, C_{N\alpha}, K_R, \bar{\delta}^2)$$

$$\ddot{Z} = f(C_X, C_{N\alpha}, K_R, \bar{\delta}^2, g)$$

5. Compute the magnitude of the slow and fast arms at the end of the integration time step

$$\lambda_F = [\frac{\rho A}{4m}][(1 - \frac{1}{\sigma})C_{N\alpha} - (\frac{md^2}{2I_y})(1 + \frac{1}{\sigma})C_{mq} - (\frac{md^2}{I_x})(\frac{1}{\sigma})C_{np\alpha}]$$

$$K_{F_{i+1}} = K_{F_i} * e^{\lambda_F * (X_{i+1} - X_i)}$$

$$\lambda_S = [\frac{\rho A}{4m}][(1 + \frac{1}{\sigma})C_{N\alpha} - (\frac{md^2}{2I_y})(1 - \frac{1}{\sigma})C_{mq} + (\frac{md^2}{I_x})(\frac{1}{\sigma})C_{np\alpha}]$$

$$K_{S_{i+1}} = K_{S_i} * e^{\lambda_S * (X_{i+1} - X_i)}$$

6. Repeat step 1 thru 5 until ground impact

During the steps reviewed above several checks and balances are made to assure computations are done within acceptable boundaries. At trajectory flight times of 0, 5, 15, 30, 50 seconds and at ground impact, the program checks for the following attributes.

- K_F, K_S , undamping, limit cycle, damping (fast / slow)
- S_g - below 1.7 , below 1.05
- Impact Range compared to expected range with zero angle of attack.

Each characteristic is tracked for trends and a simplified matrix of results is output. Figure 11 illustrates results at 15 deg-C for the XM483. The preliminary diagnosis of problems are presented by code. The codes are defined in Figure 12. In addition the details of the problems are tracked for each trajectory and may be output individually. Figure 13 illustrates this table for specific initial conditions.

XM483RNW : XM483 1974 VERSION

Expected Performance at Temperature (Deg C) = 15.0

Gun Elevation (deg)			15.0		30.0		45.0		65.0	
Velocity (m/sec)	SG(M)	ABAR (deg)	Range (m)	Status	Range (m)	Status	Range (m)	Status	Range (m)	Status
294.9	1.4	2.7	4021.	0	6538.	4	7333.	0	5571.	2
		6.6	3938.	4	6233.	4	7017.	4	5385.	4
		10.6	3701.	8	5545.	8	6052.	8	4689.	8
		15.9	3427.	8	5028.	8	5397.	8	4049.	8
334.7	1.4	2.6	4876.	0	7899.	0	8871.	2	6770.	2
		6.6	4849.	0	7829.	0	8772.	0	6689.	2
		10.6	4792.	1	7658.	4	8529.	4	6497.	4
		15.9	4560.	8	6665.	8	7094.	8	5395.	8
385.9	1.5	2.4	5522.	0	8841.	0	9967.	0	7639.	0
		6.1	5500.	0	8808.	0	9916.	0	7605.	0
		9.7	5459.	1	8732.	0	9832.	0	7528.	0
		14.6	5360.	0	8567.	0	9542.	0	7257.	9
461.5	1.5	2.4	6970.	0	10685.	0	12018.	0	9273.	0
		5.9	6944.	0	10653.	0	11983.	0	9247.	0
		9.4	6892.	1	10585.	0	11903.	0	9184.	0
		14.1	6792.	0	10458.	0	11761.	0	9054.	0
546.8	1.5	2.3	8747.	0	12832.	0	14380.	0	11188.	0
		5.8	8717.	0	12797.	0	14343.	0	11154.	0
		9.3	8659.	1	12722.	0	14262.	0	11087.	0
		14.0	8541.	0	12577.	0	14103.	0	10952.	0
648.6	1.5	2.3	10981.	0	15525.	0	17361.	0	13668.	0
		5.8	10943.	0	15478.	0	17309.	0	13621.	0
		9.2	10877.	1	15394.	0	17222.	0	13545.	0
		13.9	10743.	0	15233.	0	17041.	0	13380.	0

Figure 11. Trajectory Matrix at 15 Deg-C

Category	Probable Cause
0	No problem
1	6DOF info run (no problem)
2	Low terminal gyro
3	Slow arm limit cycle >6
4	Fast arm undamping
5	Slow arm short round
6	Fast arm short round
7	Low muzzle gyro - slow arm short round
8	Low muzzle gyro - fast arm short round
9	Problem ??? short round please run 6DOF
10	Gyro unstable at muzzle

Figure 12. Diagnostic Codes

Expected Performance at Temperature (Deg C) = 15.0

Gun Elevation (deg)			15.0		30.0		45.0		65.0	
Velocity (m/sec)	SG(M)	ABAR (deg)	Range (m)	Status	Range (m)	Status	Range (m)	Status	Range (m)	Status
294.9	1.3	2.8	4026.	0	6560.	0	7359.	2	5589.	2
		7.0	3993.	0	6506.	0	7297.	2	5539.	2
		11.2	3634.	8	5445.	8	5974.	8	4642.	8
		16.8	3350.	8	4962.	8	5312.	8	3975.	8
334.7	1.3	2.8	4863.	0	7895.	0	8872.	2	6775.	2
		7.0	4810.	0	7800.	0	8771.	2	6701.	2
		11.2	4755.	1	7683.	0	8610.	2	6541.	2
		16.8	3960.	8	5674.	8	6100.	8	4576.	8
385.9	1.4	2.5	5713.	0	9133.	0	10307.	0	7938.	2
		6.3	5691.	0	9099.	0	10265.	0	7903.	2
		10.1	5649.	1	9019.	0	10167.	0	7823.	2
		15.2	5545.	0	8865.	0	9991.	0	7679.	2
461.5	1.5	2.4	7117.	0	10945.	0	12353.	0	9601.	0
		6.1	7089.	0	10908.	0	12311.	0	9566.	0
		9.8	7035.	1	10840.	0	12233.	0	9499.	0
		14.7	6929.	0	10703.	0	12075.	0	9367.	0

Figure 13. Trajectory Diagnostics as Function of Time

b. 6DOF Simulation for Validation

After the 2DOF process is completed including preliminary diagnosis of the problem(s), the analyst(user) is afforded the opportunity to run 6DOF trajectories for validation purposes on up to 25 of the possible 384 2DOF runs. The AI-TRAJ code selects a sample of the 'worst' cases and a limited sample of acceptable flights. The user retains final authority, however, on which 6DOF's will be run through menu selection.

The angular motion history of each 6DOF executed along with other key trajectory information including impact range are stored for analysis and comparison with the previous results of the identical 2DOF trajectory. The angular motion, in the form of Yaw Sonde type plots are available for viewing and printing. Also available are velocity, spin, and gyroscopic stability factor as a function of time. Figures 14 and 15 illustrate the Yaw Sonde type plots for Supersonic and Transonic XM483 initial conditions at 30 degrees gun elevation.

The angular motion computed(6DOF) is now fit to the Linear Theory solution (Ref. 9) shown below by least squares in a manner very similiar to the technique used in Ballistic Ranges.

$$\alpha = K_F e^{\lambda_F \bar{X}} cos(\phi_F + \dot{\phi}_F \bar{X} + \ddot{\phi}_F \frac{\bar{X}^2}{2}) + K_S e^{\lambda_S \bar{X}} cos(\phi_S + \dot{\phi}_S \bar{X} + \ddot{\phi}_S \frac{\bar{X}^2}{2})$$

$$\beta = K_F e^{\lambda_F \bar{X}} sin(\phi_F + \dot{\phi}_F \bar{X} + \ddot{\phi}_F \frac{\bar{X}^2}{2}) + K_S e^{\lambda_S \bar{X}} sin(\phi_S + \dot{\phi}_S \bar{X} + \ddot{\phi}_S \frac{\bar{X}^2}{2}) + K_R$$

By Linear Theory, the resultant 6DOF motion can be analyzed with respect to the same criteria used for the 2DOF and the codes shown in Figure 12 assigned as appropriate. Tabular output in the form of Figure 13 is also available. Direct comparison of the code(s)

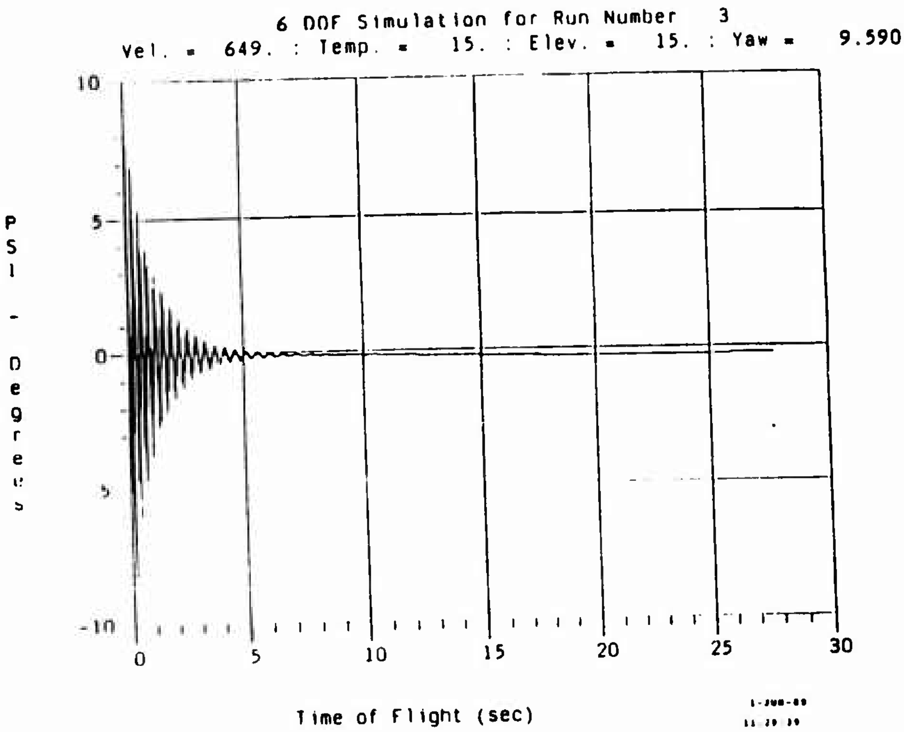

Figure 14. Supersonic Yawing Motion History - XM483

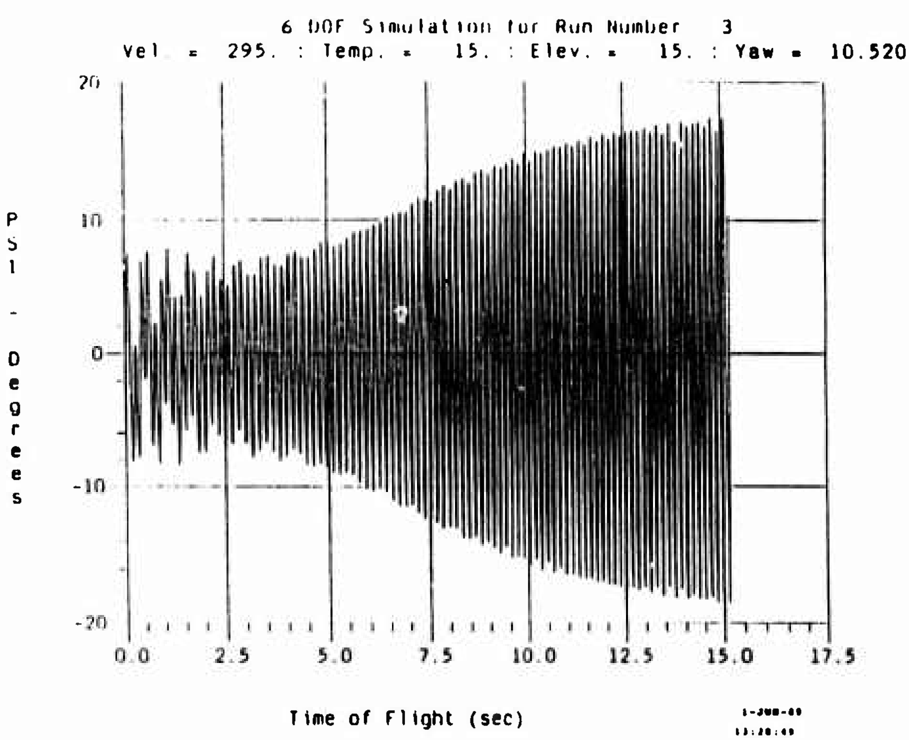

Figure 15. Transonic Yawing Motion History - XM483

and the impact ranges (2DOF vs. 6DOF) are displayed to the user. At the point, the user can elect to:

1. Change the diagnosis
2. Proceed to the AERO-AI code dicussed in the following section
3. Restart the AI-TRAJ with other initial conditions
4. Return to PRODAS without further analysis

IV. AERO-AI Artificial Intelligence / Expert System

AERO-AI is a rule-based expert system developed by GE's Advanced Technology Labs (GE-ATL) in Moorestown, NJ, under subcontract to the Armament Systems Department (GE-ASD).

AERO-AI has been implemented using Inference's Automated Reasoning Tool (ART), a powerful expert system building shell. GE-ATL has augmented the basic ART package with a number of C functions. This additional code performs tasks such as interprocess communication, input file parsing, and generation of textual user recommendations. The rule base structure of AEROAI was designed to facilitate further expansion and refinement by trained system managers.

Two versions of AEROAI have been developed. One is a Vax-based ART/C version which is invoked as a subprocess to the main PRODAS system. Communication between the two programs is performed automatically through a pair of dedicated VMS mailboxes. The second version of AEROAI is a standalone system running on a Sun workstation under ART/LISP. The C functions from the Vax version have been translated into Sun/LISP functions, but both versions use the same source code and data files. The user must transfer the AITRAJ program manually to the Sun before beginning operation. Figure 16 shows the relationship between PRODAS, AI-TRAJ, and AERO-AI.

There are four main components to the AERO-AI expert system: the rulebase, the initial factbase, the auxiliary LISP or C code, and the recommendation code definitions. All are discussed in more detail in later sections. The four components are kept in separate files within the home AERO-AI directory, as follows:

Initial Factbase:	aeroai$home:aeroai-facts.art
Rulebase:	aeroai$home:aeroai-rules.art
Auxiliary Code:	aeroai$home:aeroai.lsp
RecCodes:	aeroai$home:reccodes.aeroai

When compiled, the combined initial factbase/rulebase is contained in the file:

aeroai$home:aeroai-rules.lbin

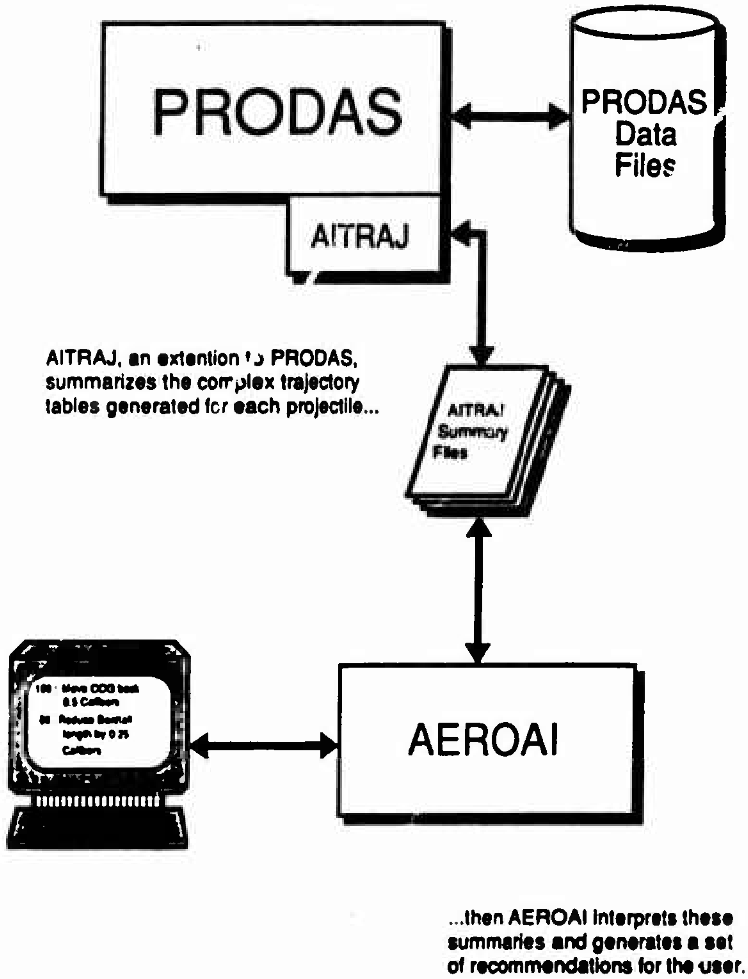

Figure 16. AERO-AI System Overview

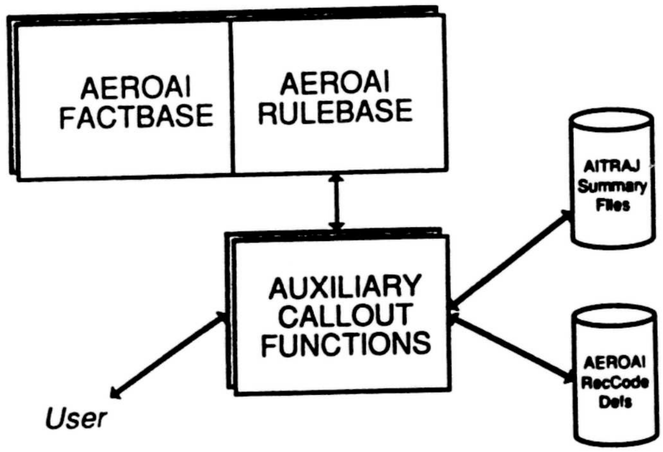

Figure 17. Componants of AERO-AI

1. ART

AERO-AI was built using ART, the Automated Reasoning Tool from Inference Corporation. ART is a commercial expert system building shell which runs on many different hardware systems. Readers unfamiliar with ART are strongly encouraged to consult "The ART Programming Tutorial" (copyright 1987, Inference Corporation), a four-volume series on the implementation of expert systems.

AERO-AI was developed using the full, standard version of ART. Inference also offers a package called "ART-IM", which is smaller and less expensive than the full version but which does not offer some of the most sophisticated expert system building constructs. AERO-AI uses only those constructs common to full ART and ART-IM.

2. Implementation Notes

This subsection discusses the internal structure of AERO-AI and the motivation behind some of the implementation decisions. Figure 17 illustrates the top-level components of AERO-AI and their interrelationships.

a. AERO-AI Rulebase Architecture

One common criticism of rule-based expert systems is that they are inherently unstructured in nature. Established languages such as FORTRAN and C have time-tested sets of rules which define good programming practice (e.g., "Avoid GOTO statements", "Put RETURN statements only at the end of a function", "Indent loop blocks two spaces", etc.), but expert system languages have few such guidelines. In addition, it is usually very

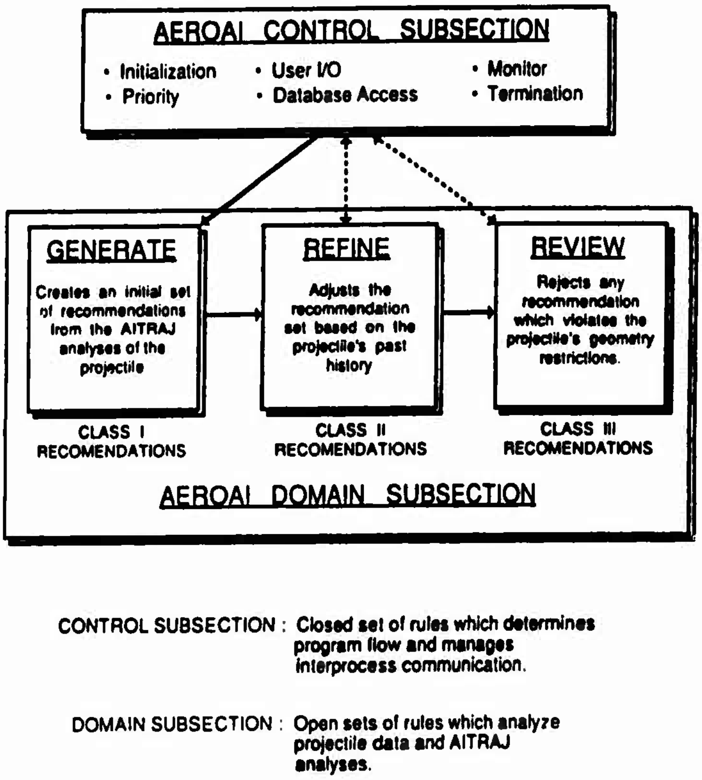

Figure 18. AERO-AI Rulebase Architecture

difficult for a reader to predict the flow of control through a rule base by simply examining the source code. The result: even well-commented expert systems are often very difficult to maintain, especially by people other than the original programmer.

AERO-AI's rulebase was developed to facilitate later maintenance and expansion. Rules that perform similar functions are grouped into blocks called "partitions", with each partition assigned a unique "salience" (i.e., priority) value. Only three partitions contain PRODAS-specific information (see Figure 18). Execution proceeds in a well-defined linear path across partitions, from highest to lowest salience. The nine partitions, in order of priority, are:

1. Initialization - performs actions necessary when the expert system is first invoked.
2. Special Priority - includes blocks of very-high-priority control rules that must be executed as an uninterrupted unit.
3. User Interface - handles communication between the expert system and the user
4. Database Query - handles communication between the expert system and any external datafiles
5. Monitor - controls execution and information flow within the domain rules.
6. Generate - creates an initial set of recommendations from the AITRAJ analyses of the projectile.

7. Refine - adjusts the recommendation set based on the projectile's past history.
8. Review - rejects any recommendation that violates the projectile's geometry restrictions.
9. Termination - performs any actions necessary before the expert system concludes operation.

These partitions are further grouped into two subsections, called Control and Domain. The Control Subsection (CS) is comprised of the Initialization, Priority, User Interface, Database Query, Monitor, and Termination partitions. Rules in the CS perform administrative and supervisory functions only; they do not contain any rules for analyzing projectiles or making recommendations. These tasks are performed by the Domain Subsection (DS), which contains all PRODAS-specific knowledge. The DS is made up of the Generate, Refine, and Review partitions.

The Control Subsystem is intended to be a "closed" set of rules, meaning that it is very unlikely any of its partitions will need to be extended in the future. The Domain Subsection, in contrast, contains an "open" set of rules. The more rules that are added to the DS, the more types of trajectory problems AERO-AI can handle, and hence the more powerful the expert system will become.

b. Recommendation Codes

A Recommendation Code (RecCode, for short) is a short mnemonic that represents the text of a user recommendation within the AERO-AI rule base. It would be both inelegant and inefficient to put the actual recommendation text within an ART rulebase source file. The most compelling reason against this is that minor grammatical or punctuation changes in a message would require a complete recompilation of the expert system.

RecCodes are defined by an external data file in the home AERO-AI directory. They are loaded into the expert system at run time. An example of a typical RecCode definition is as follows:

%RECCODE MOVE_COG_FOR

0 - "Move center of gravity towards front of projectile"

1 - "Move center of gravity ,3F calibers towards front of projectile"

This defines the recommendation code MOVE_COG_FOR ("MOVE C-O-G FORward"), corresponding to the two text strings listed above. The numbers preceding the strings represent the number of arguments within the text. This is called the "arity" of the string, and RecCodes are generally referred to as MNEMONIC/ARITY (for example, "REDC_BT_LEN/0" represents the Reduce Boattail Length recommendation with zero arguments).

RecCodes are defined starting with the introductory symbol "%RECCODE" and the name of the mnemonic ("MOVE_COG_FOR"), in the example). Next, the strings corresponding to each legal arity are given, one arity/string per line. The string is delimited by double quotes, and a space-hyphen-space separates the arity from the string.

Those familiar with LISP will recognize the MOVE_COG_FOR/1 to be a template for the FORMAT function in Common LISP. The " ,3F" represents the printed representation of a floating-point number taken to three decimal places. Indeed, AERO-AI uses FORMAT to generate the actual messages it presents to the user. Given the ART clause...

(recommendation (TEST 3) F MOVE_COG_FOR (0.1295) 95)

...AEROAI will print a text recommendation for projectile TEST, revision 3, of the form...

95 : Move center of gravity 0.130 calibers towards front of projectile.

A double-tilde within the text string corresponds to a carriage return in the printout. This differs from Common LISP standard, where a double-tilde specifies a single tilde in the output stream.

Information Codes (InfoCodes) are the corresponding mnemonics for Informational Messages. They are kept in the same external data file as RecCodes and are used in an analogous manner. InfoCodes are introduced in the RecCode file by the symbol "%INFOCODE" rather than "%RECCODE", but otherwise are defined similarly.

c. AERO-AI Facts File and Initial Factbase

The AERO-AI facts file defines the relations and global variables which are used in the rulebase. Together with the rulebase file, it acts as the source code for the expert system. The facts file must be loaded into ART before the rulebase is loaded, compiled, and saved.

The facts file is divided into three sections: definition of relations, definition of global variables, and the Initial Factbase. The first two sections roughly correspond to defining constants and variables in a PASCAL program, and they are of little interest to the user.

The Initial Factbase is the set of facts that are present at the start of an AERO-AI run. In general, these are special relations which define how AERO-AI should handle certain situations.

- (ASP-ZONING (threshold) (init-wt) (incr-wt))
  - Specifies when AERO-AI will recommend the Zoning Option to the user. If the projectile gets "stuck" in failure classes 5, 6, 7, or 8 for (threshold) consecutive PRODAS runs, then AERO-AI recommends the Zoning Option with a weighting factor of (init-wt). Each unsuccessful run thereafter increases the weight by (incr-wt).
- (THRESHOLD (dimension) (min-chng))
  - Specifies the minimum change in geometry metric (dimension) that is considered significant by AERO-AI. For example, the fact (THRESHOLD VB .01) specifies

that a projectile's boattail length must be increased or decreased by at least 1have a measurable impact on performance.

- (VB-OSCILLATION (fc1) (fc2) (reccode) (direction) (message) (wt))
  - The "Boattail Oscillation" relation. Adjusting the boattail length of a projectile will often cause it to jump from one major failure class to another. This relation alerts AERO-AI to the cases when such a jump might have taken place, and the expert system can adjust its recommendations accordingly in the Refine partition. What this relation does is prevent AERO-AI from recommending on one run "Move the boattail up .25 calibers", then on the very next run recommending "Move the boattail back .25 calibers", ad infinitum. Users have been found to become quite irate when an expert system exhibits such behavior.
  - As an example, consider the fact:
    (VB-OSCILLATION 7 6 INCR_BT_LENGTH - OSC_VB_NEG 95)
    Whenever AERO-AI is about to make an "INCR_BT_LENGTH" recommendation for a projectile with Failure Code 7, it will first check to see if the boattail was reduced (the "-" argument; also may be written "NEGATIVE") in response to an earlier Failure Code 6. If so, the recommendation should be refined (usually by splitting the difference between the boattail lengths) and an "OSC_VB_NEG" Information Message should be printed with weighting factor 95.
- (GEOMETRY-METRIC (reccode) (metric) (direction))
  - Specifies what geometry metrics are affected by a particular recommendation, and whether they will increase or decrease. For example, (GEOMETRY-METRIC INCR_BT_LENGTH VL +) states that the total length of the projectile (VL) will increase (+) in response to an INCR_BT_LENGTH recommendation. These facts are used in the Review partition when checking geometry restrictions.

d. Auxiliary LISP/C Code

ART includes a powerful feature called the "callout" utility. This allows a programmer to invoke external functions or procedures from within a rule base, either on the left-hand or right-hand side of a rule. Such functions might perform complicated mathematical calculations (something Common LISP in general and ART in particular is notoriously poor at doing), handling I/O, and manipulating strings. It is good programming practice to do as much algorithmic work as possible using auxiliary code, leaving ART to handle control and heuristic tasks.

AERO-AI includes a number of callout functions encoded in both C (for the Vax version) and LISP (for the Sun version). The most important of these include:

- load-AEROAI-table (proj, rev) : Loads the AI-TRAJ summary file for a given projectile and revision number.
- send-user (msg, color) : Displays a message to the the user.

- recommend (type, msg, wt) : Generates a recommendation or informational message to the user and assigns it a specific weighting factor.
- prodas-request (req) : Requests that PRODAS take some action and send the results back to the expert system. (On the standalone Sun version, this function simply initiates the sequence that displays AERO-AI's recommendations to the user).
- save-recommendations ( ) : Writes the current set of recommendations to a disk file.

3. AERO-AI Operation

This section discusses the operation of AERO-AI and the steps it takes in evaluating a projectile. Interpreting the output of the system is covered in subsection .

a. AERO-AI Flow of Execution

To illustrate the execution path that AERO-AI takes in evaluating a projectile, consider a sample consultation session. Assume that AERO-AI has been invoked (in either the Vax/C or Sun/LISP version) and is sitting in an idle state waiting for the user's instructions (refer to Figure 19, throughout this section, starting at step 0).

Execution begins when AERO-AI receives a request to evaluate a particular design. Depending on which version is run, this may be through an explicit "EVALUATE" command issued by the user, or via a text message received directly from PRODAS. AERO-AI awakens (Special Priority partition, step 1), and control then passes to the Monitor (step 2).

The Monitor performs three major tasks. First, it creates the internal control relations specifying the current projectile-name and revision number. Second, it checks if the AITRAJ datafiles for the current projectile/revision and all its previous revisions have been loaded into the fact base. If not, control temporarily passes to the Database Query partition which loads the necessary files (Step 2a). Third, it decides which of the two temperature analyses - COLD or AMBIENT - should be evaluated.

In general, it is best to concentrate on the worse of the two analyses. This is because solving the more serious problem often results in eliminating the less serious one also. If both analyses have the same failure code, the COLD analysis should be used. Note that this is the only PRODAS-specific knowledge that is encoded outside of the Domain Subsection.

Control now moves to the Domain Subsection, Generate partition (step 3). Here, the current projectile/revision is evaluated independent of any past revisions or geometry restrictions. The end result is a set of initial, or "Class I", recommendations. Figure 20 presents a partial list of recommended actions by 'Problem Code'.

The Refine partition (step 4) will review the projectile's previous revisions and determine if any Class I recommendations should be retracted or adjusted. Rules in this

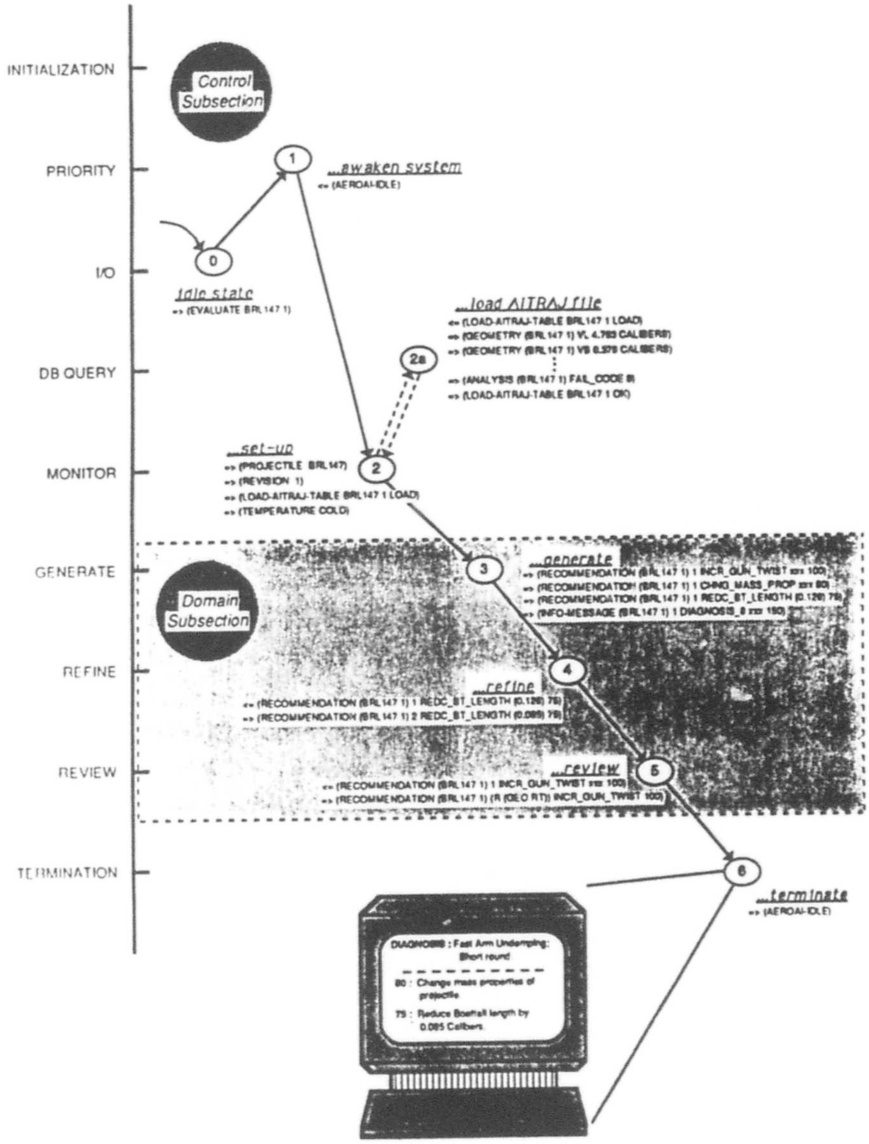

Figure 19. Flow of Execution in AERO-AI

```
Error 2     Low Terminal Gyroscopic Stability
      o Incease the rifling twist
      o Increase axial inertia

Error 4     Fast Arm Limit Cycle
      o Move center of gravity towards rear of projectile
      o Decrease boat tail length (if greater than .25 calibers)
        This recommendation will not be presented on the first pass
        through the program because of the resulting increased drag.

Error 6     Fast Arm Short Round
      o Move center of gravity towards rear of projectile
      o Decrease boat tail length (if greater than .25 calibers)
        This recommendation will not be presented on the first pass
        through the program because of the resulting increased drag.

Error 8     Low Muzzle Gyroscopic Stability - fast arm short round
      o Incease the rifling twist
      o Move center of gravity forward
      o Increase axial inertia
      o Decrease transverse inertia
      o Decrease boat tail length (if greater than .25 calibers)
        This recommendation will not be presented on the first pass
        through the program because of the resulting increased drag.

Error 10    Gyroscopic instability at the Muzzle
      o Incease the rifling twist
      o Move center of gravity forward
      o Increase axial inertia
      o Decrease transverse inertia
      o Decrease boat tail length (if greater than .25 calibers)
        This recommendation will not be presented on the first pass
        through the program because of the resulting increased drag.
```

Figure 20. Recommended Actions

section look for dangerous trends across several runs. For example, if a projectile oscillates between certain failure classes for several consecutive revisions, this might be indicative of a more serious design flaw. In addition, rules in this partition check to see if any Class I recommendations for the projectile have already been attempted and rejected by the user.

The revised set of "Class II" recommendations are passed to the Review partition for final analysis (step 5). Here, AERO-AI checks to see if any recommendation violates the set of geometry restrictions specified by the user. If so, the recommendation is "flagged" (rather than flatly retracted) and will be displayed only after the set of Final Recommendations are presented to the user.

In all three Domain Subsection partitions, "informational messages" are occasionally generated by AERO-AI. These messages are not considered formal recommendations per se, but rather diagnoses, warnings, data summaries and other information that might be valuable to the user. All output from AERO-AI (both messages and recommendations) are assigned a weighting factor that determines the order in which they are displayed to the user.

Finally, AERO-AI returns to the Control Subsection in the Termination partition (step 6), where the DISPLAY-RECOMMENDATIONS function is invoked. AERO-AI first displays any informational messages generated during the current run, followed by the set final recommendations, followed by any recommendations which were rejected due to geometry restrictions in the Review partition. AERO-AI then returns to its idle state to await further instructions.

b. AERO-AI Output Messages

Consider a sam ·le AERO-AI user recommendation:

100 : Reduce the projectile's boattail length by approximately 0.25 calibers.

The two numbers present in this message are very significant and easily misunderstood. The first number, 100, is the recommendation's "weighting factor". It specifies the relative importance of each message, and it is used to determine the order in which a set of recommendations are displayed to the user. It should absolutely NOT be construed as either a "confidence value" or the percentage chance of success, especially since weighting factors will often exceed 100. A weighting factor of 80, for example, simply means that a PRODAS expert would be more likely to make this recommendation to a novice user than he would one of 60.

If a recommendation contains an explicit adjustment value ("0.25 calibers" in the example), this number should be taken as a general guideline only. The user may choose a larger adjustment, or a smaller adjustment, or maybe even no adjustment at all. As when using any expert system, the user should rely on his own judgment as the final arbiter.

c. Extending AERO-AI

As stated earlier, virtually all future additions to the AERO-AI rulebase will be made in the Domain Subsection. AERO-AI users are encouraged to extend the expert system by writing their own custom rules. Appendix C contains a step-by-step guide to customizing AERO-AI.

V. Conclusions

The PRODAS program with AI-TRAJ enhancements has been installed on a VAX computer and the companion program AERO-AI has been installed a SUN workstation at the BRL. The PRODAS code with AI-TRAJ has been extensively utilized and tested at GE-ASD and Arrow Tech. This code is capable of:

- Improved aerodynamic coefficient prediction for spin stabilized projectiles
- Automatically executing a matrix of trajectories (2DOF modified)
  - Muzzle Velocities (8 zones Maximum)
  - Gun Elevations (4 maximum)
  - Atmospheres (cold, ambient, hot)
  - In-bore yaw angles (4 maximum)
- Determination of short range problems (2DOF with Linear Theory)
- Diagnosis of stability problems (2DOF with Linear Theory)
- Automatic execution of selected trajectories by 6DOF
- Automatic comparison of 2DOF and 6DOF results
- Confirmation of 2DOF problem diagnosis
- Interface with AI recommendation codes
- Maintains Log of problems, recommendations, and results

References

1. Burnett, J.R.,and Et Al, "PROjectile Design and Analysis System (PRODAS) Technical Manual," General Electric Armament Systems Dept., April 1987.

2. Fischer, M.A., "PRODAS User Manual - Version 3.1," General Electric Armament Systems Dept., February 1989.

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4. Whyte, R.H., "SPIN-73 An Updated Version of the SPINNER Computer Program," Picatinny Arsenal TR 4588, November 1973.

5. Whyte, R.H., Burnett, J.R., and Hathaway, W.H., "FIN-81 A Computer Program to Predict Fin Stabilized Projectile Aerodynamic Coefficients and Stability Parameters," General Electric Armament Systems Dept., April 1981.

6. McShane, Kelly, and Reno," Exterior Ballistics, " University of Denver Press, 1953.

7. Whyte, R.H., and Et Al, "Two / Six Degree of Freedom Trajectory Computer Program," General Electric Armament Systems Dept., 1971, Revised 1984.

8. Wong, B.C., Burnett, J.R., and Hathaway, W.H., "Users Manual for Firing Table Program," General Electric Armament Systems Dept., February 1986.

9. Murphy, C.H., "Free Flight Motion of Symmetric Missiles," Ballistic Research Laboratories Report 1216 , July 1963.

10. "The ART Programming Tutorial," Inference Corporation, 1987.

11. Harmon, P., Maus, R., and Morrissey, W.," Expert Systems - Tools & Applications," John Wiley & Sons, 1988.

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List of Symbols

A	$\pi d^2/4$, reference area
C_X	$\lvert axial\ force \rvert /[(1/2)\rho AV^2]$
C_{X_0}	the zero-yaw axial force coefficient
$C_{X_{\delta^2}}$	the yaw-axial force coefficient; the slope of C_X versus δ^2
C_{ℓ_p}	$\pm \lvert roll\ damping\ moment \rvert /[(1/2)\rho AdV^2(pd/(2V))]$
C_{ℓ_δ}	$\pm \lvert roll\ moment\ due\ to\ canted\ fins \rvert /[(1/2)\rho AdV^2\delta_f]$
$C_{n_{p\alpha}}$	$\pm \lvert Magnus\ moment \rvert /[(1/2)\rho AdV^2(pd/(2V))\delta]$
C_{m_q}	$\pm \lvert damping\ moment\ sum \rvert /[(1/2)\rho AdV^2(qd/2V))]$
C_{m_α}	$\pm \lvert static\ moment \rvert /[(1/2)\rho AdV^2\delta]$
$C_{Y_{p\alpha}}$	$\pm \lvert Magnus\ force \rvert /[(1/2)\rho AV^2(pd/2V))\delta]$
C_{N_α}	$\pm \lvert normal\ force \rvert /[(1/2)\rho AV^2\delta]$
CPN	center of pressure of the normal force (calibers from the nose)
d	reference length: the representative missile diameter
d_b	gun-bore diameter
g	gravity acceleration
I_x, I_y	the missile's axial and transverse moments of inertia
k_a	$\sqrt{I_x/md^2}$, the axial radius of gyration
k_t	$\sqrt{I_y/md^2}$, the transverse radius of gyration
K_F, K_S	lengths of the yaw fast and slow arms
K_R	the yaw of repose
m	missile mass
M	Mach number

p, q, r	components of the missile's angular velocity
S_g	The gyroscopic stability factor, gyroscopic instability occurring when $0 < S_g < 1$
t	time
u, v, w	missile velocity components
V	missile velocity
X, Y, Z	range coordinates, a right-handed system with X positive down-range Y positive left and Z positive upward.
$\bar{X}$	$\int V\,dt$, arclength along the trajectory
$\bar{\alpha}$	the total angle of attack, $\arccos(u/V)$
α	Missile pitch angle, $\arctan w/u$
β	Missile yaw angle, $\arctan v/u$
γ	Trajectory angle to earth
ζ	$\sin\bar{\alpha}$
$\bar{\delta}^2$	mean-squared yaw: $\geq K_F^2 + K_S^2$
δ_f	fin cant angle
λ_F, λ_S	damping rates of the yaw fast and slow arms
ρ	air density
ϕ	roll angle
ϕ_F, ϕ_S	polar angles of the yaw Fast and Slow arms
$\dot{\phi}_F, \dot{\phi}_S$	turning rates of the yaw Fast and Slow arms

APPENDIX A.

AI PRODAS XM483 Sample Output

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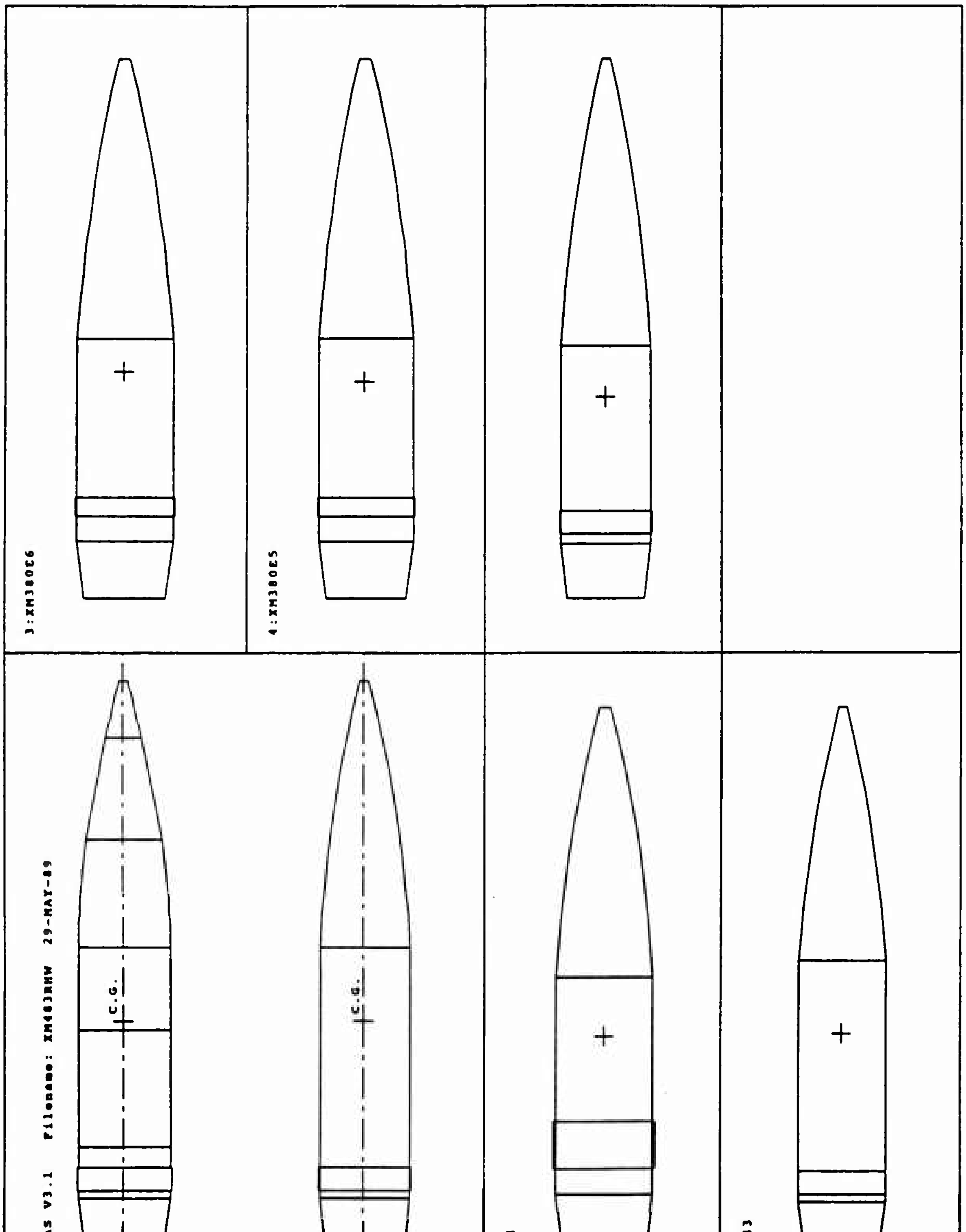
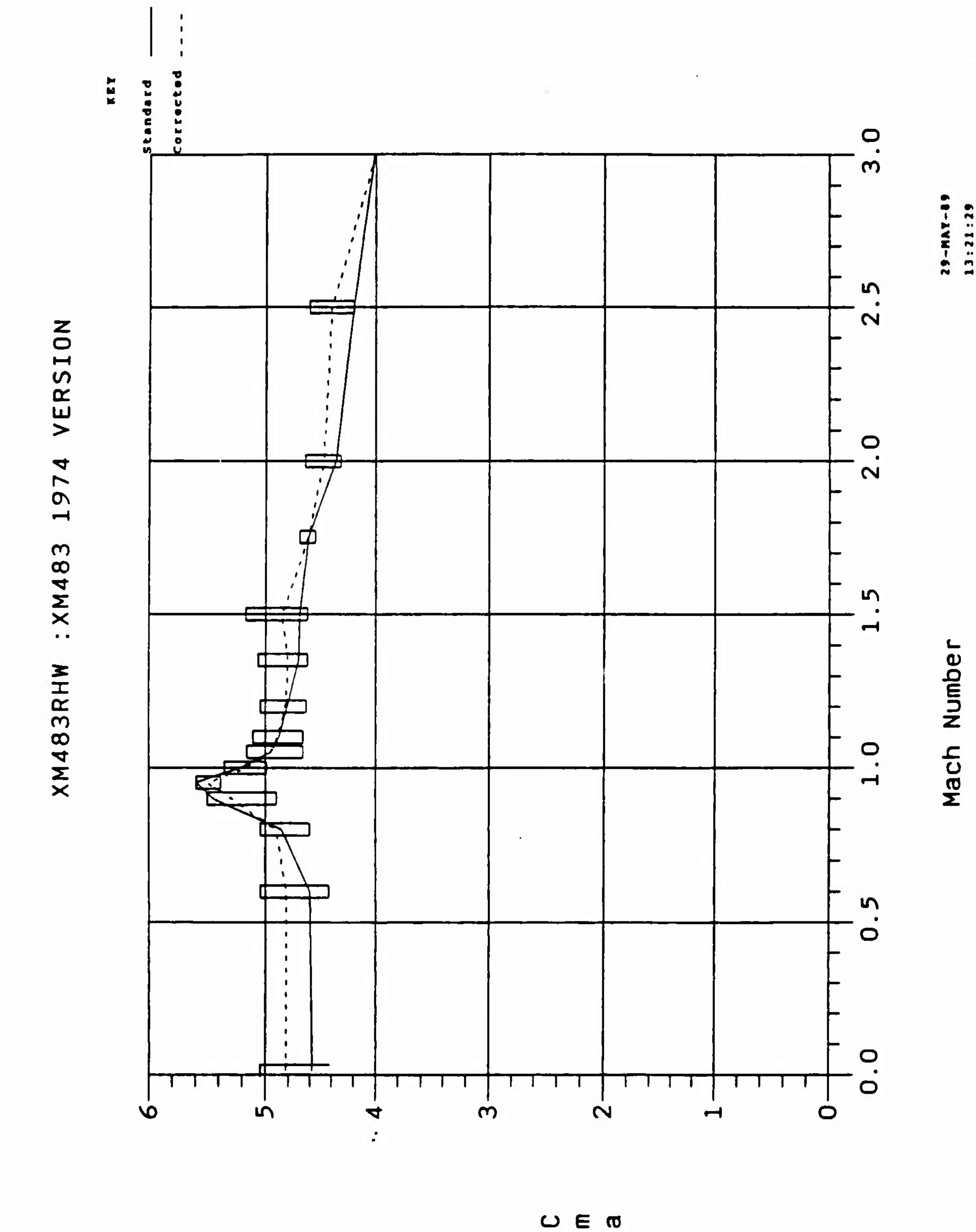
Select which projectiles to include in the computation of the probable error.
Include flag is at the end on each entry
1 for Include flag mean projectile is used
0 for Include flag mean projectile is not used

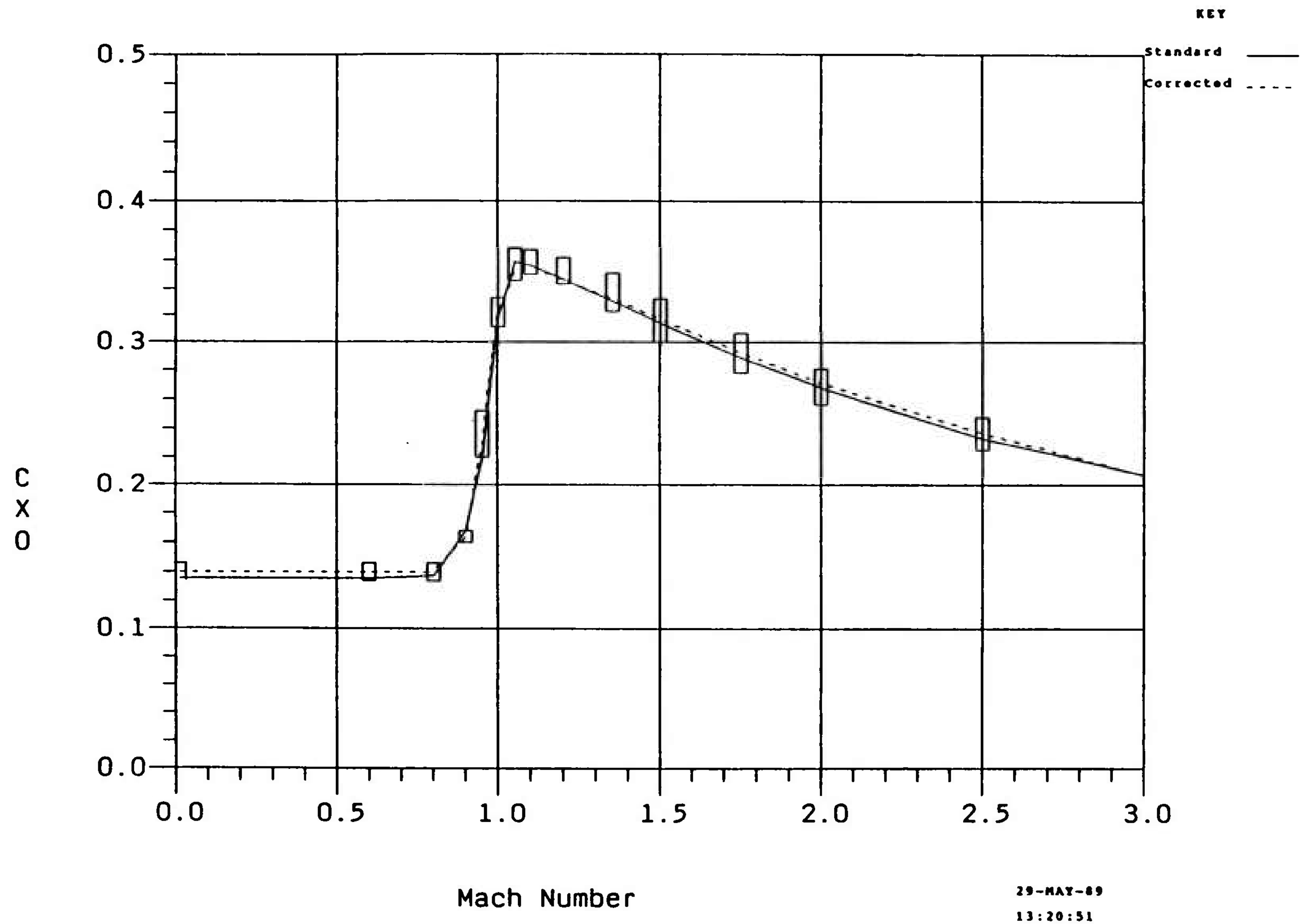
Round Designation	Total Length	Ogive Length	Boat Tail Length	CG from Nose	Ogive Radius	Meplat Diameter	Boom Length	Diameter (mm)
1 - 5/54	5.26	2.63	0.52	3.21	13.0	0.11	0.00	126.62 - 1
2 - XM483	6.05	2.84	0.51	3.66	15.3	0.10	0.00	154.74 - 1
	6.05	2.85	0.51	3.66	15.3	0.10	0.00	154.69
3 - XM380E6	5.58	2.90	0.59	3.24	18.6	0.13	0.00	104.83 - 1
4 - XM380E5	5.58	2.90	0.59	3.34	18.6	0.13	0.00	104.83 - 1
5 - M549	5.64	3.01	0.58	3.53	18.9	0.10	0.00	154.74 - 1


PRODAS V3.1 Filename: XM483RHW 29-MAY-89
C.G.
C.G.
1:5/54
2:XM483
3:XM380E6
4:XM380E5



XM483RHW :XM483 1974 VERSION
KEY
Standard
Corrected
C m a
Mach Number
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0
1
2
3
4
5
6
29-MAY-89
13:21:29

XM483RHW :XM483 1974 VERSION



Filename: XM483RHW 29-MAY-89 :XM483 1974 VERSION

Stability Results

	Projectile Length	Ogive Length	Boattail Length	Boom Length	C.G. from Nose	Band Diameter	Meplat Diameter	Ogive Radius	Rifling Twist
in mm	936.244	440.182	78.867	0.000	566.151	157.988	15.240	2366.696	3101.340/rev
in calibers	6.053	2.846	0.510	0.000	3.660	1.021	0.099	15.300	20.000/rev

Diameter (mm)	Weight (kg)	Gun Bore (mm)	Temperature (Deg C)	Air Density (gm/cm**3)	Axial Mom. (kg-cm**2)	Trans. Mom. (kg-cm**2)
154.686	46.266	155.067	15.000	0.001225	1492.46399	17851.03906

Aerodynamic Coefficients

Spinner Prediction

Mach	CX	CX2	CNa	Cma	CPN	CYpa	Cnpa-0	Cnpa-2	Cnpa-5	Cnpa-10	Cnpa3	Cnpa5	Cmq	Clp
0.010	0.133	2.689	1.800	4.755	1.018	-1.019	-0.397	0.053	0.903	1.03	170.77	-4035.	-10.1	-0.031
0.600	0.133	2.689	1.800	4.755	1.018	-1.019	-0.397	0.053	0.903	1.03	170.77	-4035.	-10.1	-0.031
0.800	0.133	3.182	1.800	5.005	0.879	-1.019	-0.597	-0.197	1.103	1.12	154.86	-3618.	-10.1	-0.031
0.900	0.160	3.703	2.000	5.407	0.956	-1.140	-0.197	1.003	2.003	1.42	109.78	-2131.	-16.1	-0.031
0.950	0.222	4.214	2.100	5.400	1.088	-1.443	1.004	1.904	2.504	1.83	82.34	-1200.	-22.1	-0.029
1.000	0.333	4.706	2.100	5.199	1.184	-1.322	0.704	1.004	1.254	1.26	59.17	-1187.	-23.1	-0.028
1.050	0.367	5.193	2.099	5.041	1.259	-1.201	0.754	0.954	1.154	1.02	36.53	-826.	-25.1	-0.028
1.100	0.367	5.766	2.149	4.941	1.361	-1.140	0.803	0.903	1.053	0.99	25.66	-548.	-27.1	-0.028
1.200	0.361	6.349	2.299	4.840	1.555	-1.019	0.803	0.853	0.953	0.93	18.03	-362.	-29.1	-0.028
1.350	0.351	5.783	2.399	4.750	1.680	-1.019	0.803	0.803	0.903	0.93	14.85	-278.	-29.1	-0.027
1.500	0.331	5.191	2.499	4.721	1.771	-1.019	0.803	0.803	0.853	0.94	13.26	-237.	-29.1	-0.027
1.750	0.306	4.616	2.624	4.692	1.872	-1.019	0.804	0.804	0.804	0.94	11.67	-195.	-29.1	-0.026
2.000	0.281	4.005	2.749	4.642	1.972	-1.019	0.804	0.804	0.804	0.95	10.08	-153.	-29.1	-0.026
2.500	0.247	3.308	2.850	4.595	2.048	-1.019	0.804	0.804	0.804	0.95	8.49	-111.	-29.1	-0.025
3.000	0.207	2.785	2.844	4.011	2.250	-1.019	0.799	0.838	0.847	0.94	6.89	-70.	-35.0	-0.025
4.000	0.169	2.312	2.744	3.952	2.220	-1.019	0.798	0.837	0.846	0.94	6.89	-70.	-34.9	-0.025
5.000	0.147	1.840	2.644	3.887	2.190	-1.019	0.795	0.834	0.844	0.94	6.89	-70.	-34.8	-0.024
6.000	0.131	1.647	2.594	3.866	2.170	-1.019	0.794	0.832	0.842	0.94	6.89	-70.	-34.7	-0.024
8.000	0.121	1.561	2.564	3.847	2.160	-1.019	0.793	0.831	0.841	0.94	6.89	-70.	-34.7	-0.023
10.000	0.114	1.467	2.544	3.842	2.150	-1.019	0.792	0.831	0.841	0.94	6.89	-70.	-34.6	-0.022

Filename: XM483RHW 29-MAY-89 :XM483 1974 VERSION

MCDRAG Computed Drag Coefficients

Projectile Length (cal):	6.05	Nose Length (cal):	2.85
Boat Tail Length (cal):	0.51	Band Diameter (cal):	1.02
CG from Nose (cal):	3.66	Diameter (mm):	154.686
Boat Tail Diameter (cal):	0.87	Meplat Diameter (cal):	0.099
Tangent / Ogive Radius :	0.04	Boundary Layer Code :	T / T

Mach	CD0	CX	DELTA	CDH	CDSF	CDBND	CDBT	CDB
0.010	0.144	0.133	0.010	0.000	0.058	0.000	0.000	0.086
0.600	0.146	0.133	0.012	0.000	0.056	0.000	0.000	0.090
0.800	0.152	0.133	0.018	0.000	0.053	0.001	0.000	0.098
0.900	0.162	0.160	0.002	0.000	0.051	0.006	0.003	0.102
0.950	0.203	0.222	-0.019	0.025	0.050	0.011	0.013	0.104
1.000	0.316	0.333	-0.017	0.049	0.050	0.010	0.069	0.138
1.050	0.380	0.367	0.012	0.129	0.049	0.010	0.055	0.137
1.100	0.354	0.367	-0.014	0.117	0.049	0.009	0.043	0.136
1.200	0.342	0.361	-0.019	0.106	0.047	0.009	0.045	0.135
1.350	0.328	0.351	-0.023	0.099	0.046	0.008	0.044	0.131
1.500	0.312	0.331	-0.019	0.095	0.044	0.007	0.039	0.127
1.750	0.289	0.306	-0.018	0.089	0.041	0.006	0.032	0.119
2.000	0.268	0.281	-0.013	0.085	0.039	0.006	0.028	0.111
2.500	0.234	0.247	-0.013	0.079	0.035	0.005	0.022	0.092
3.000	0.205	0.207	-0.002	0.075	0.032	0.005	0.017	0.076
4.000	0.164	0.169	-0.005	0.069	0.027	0.005	0.012	0.051
5.000	0.138	0.147	-0.010	0.065	0.023	0.005	0.009	0.035

*** CX is either Spinner or modified drag ***
*** coefficient as presented in the above table ***

Filename: XM483RHW 29-MAY-89 :XM483 1974 VERSION

Stability Parameters (Page 1)

Mach	GYRO	SBAR	RECIP	SBAR-5	RECIP-5	Spin (rad/sec)	DELT (sec)	DISP (mrad)
0.01	1.516	0.082	6.333	2.147	-3.162	7.	0.6879	0.010
0.60	1.516	0.082	6.333	2.147	-3.162	414.	0.0115	0.010
0.80	1.440	-0.235	-1.903	2.465	-0.873	552.	0.0088	0.009
0.90	1.333	0.331	1.810	2.765	-0.473	621.	0.0081	0.010
0.95	1.335	1.301	1.100	2.593	-0.650	655.	0.0076	0.010
1.00	1.386	0.993	1.000	1.457	1.263	690.	0.0071	0.010
1.05	1.430	0.963	1.001	1.279	1.085	724.	0.0067	0.010
1.10	1.459	0.946	1.003	1.130	1.017	759.	0.0063	0.010
1.20	1.489	0.907	1.009	1.009	1.000	828.	0.0058	0.011
1.35	1.517	0.917	1.007	0.985	1.000	931.	0.0051	0.012
1.50	1.527	0.929	1.005	0.962	1.001	1034.	0.0046	0.013
1.75	1.536	0.943	1.003	0.943	1.003	1207.	0.0039	0.014
2.00	1.553	0.957	1.002	0.957	1.002	1379.	0.0034	0.015
2.50	1.569	0.969	1.001	0.969	1.001	1724.	0.0027	0.016
3.00	1.797	0.836	1.028	0.862	1.019	2069.	0.0022	0.019
4.00	1.824	0.832	1.029	0.859	1.020	2758.	0.0016	0.018
5.00	1.854	0.826	1.031	0.853	1.022	3448.	0.0013	0.018
6.00	1.864	0.823	1.032	0.851	1.023	4138.	0.0011	0.018
8.00	1.874	0.821	1.033	0.849	1.023	5517.	0.0008	0.018
10.00	1.876	0.820	1.034	0.847	1.024	6896.	0.0006	0.018

Filename: XM483RHW 29-MAY-89 :XM483 1974 VERSION

Stability Parameters (Page 2)

Mach Number	Nutation Freq. W1 (deg/m)	(rad/sec)	Damping at angle (degrees) L1-0 (1/m)	L1-2 (1/m)	L1-5 (1/m)	L1-10 (1/m)
0.01	7.683	0.	-0.00152	-0.00081	0.00054	0.00073
0.60	7.683	27.	-0.00152	-0.00081	0.00054	0.00073
0.80	7.535	36.	-0.00191	-0.00124	0.00093	0.00097
0.90	7.278	39.	-0.00197	0.00024	0.00209	0.00102
0.95	7.282	41.	-0.00044	0.00122	0.00232	0.00108
1.00	7.414	44.	-0.00111	-0.00059	-0.00015	-0.00013
1.05	7.513	47.	-0.00125	-0.00091	-0.00057	-0.00080
1.10	7.574	49.	-0.00137	-0.00121	-0.00096	-0.00107
1.20	7.633	54.	-0.00157	-0.00149	-0.00133	-0.00137
1.35	7.686	62.	-0.00156	-0.00156	-0.00140	-0.00136
1.50	7.702	69.	-0.00155	-0.00155	-0.00147	-0.00134
1.75	7.719	80.	-0.00154	-0.00154	-0.00154	-0.00132
2.00	7.747	92.	-0.00153	-0.00153	-0.00153	-0.00131
2.50	7.774	115.	-0.00152	-0.00152	-0.00152	-0.00130
3.00	8.084	144.	-0.00209	-0.00204	-0.00203	-0.00189
4.00	8.113	193.	-0.00209	-0.00203	-0.00202	-0.00189
5.00	8.146	242.	-0.00208	-0.00203	-0.00201	-0.00188
6.00	8.156	291.	-0.00208	-0.00202	-0.00201	-0.00188
8.00	8.166	388.	-0.00208	-0.00202	-0.00201	-0.00188
10.00	8.168	485.	-0.00208	-0.00202	-0.00201	-0.00188

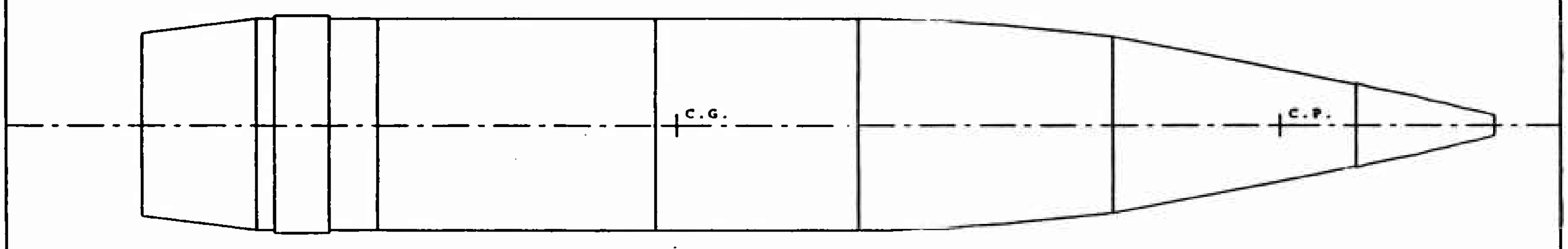
Filename: XM483RHW 29-MAY-89 :XM483 1974 VERSION

Stability Parameters (Page 3)

Mach Number	Precession Freq. W2 (deg/m)	(rad/sec)	Damping at angle (degrees) L2-0 (1/m)	L2-2 (1/m)	L2-5 (1/m)	L2-10 (1/m)
0.01	2.022	0.	0.00030	-0.00041	-0.00176	-0.00195
0.60	2.022	7.	0.00030	-0.00041	-0.00176	-0.00195
0.80	2.170	10.	0.00068	0.00001	-0.00216	-0.00219
0.90	2.427	13.	0.00024	-0.00198	-0.00382	-0.00275
0.95	2.422	14.	-0.00178	-0.00344	-0.00455	-0.00330
1.00	2.291	14.	-0.00119	-0.00171	-0.00215	-0.00217
1.05	2.192	14.	-0.00121	-0.00155	-0.00188	-0.00165
1.10	2.131	14.	-0.00125	-0.00141	-0.00166	-0.00155
1.20	2.071	15.	-0.00124	-0.00132	-0.00148	-0.00145
1.35	2.019	16.	-0.00128	-0.00128	-0.00144	-0.00148
1.50	2.002	18.	-0.00131	-0.00131	-0.00139	-0.00152
1.75	1.986	21.	-0.00136	-0.00136	-0.00136	-0.00157
2.00	1.958	23.	-0.00140	-0.00140	-0.00140	-0.00162
2.50	1.931	29.	-0.00143	-0.00143	-0.00143	-0.00165
3.00	1.621	29.	-0.00131	-0.00137	-0.00138	-0.00152
4.00	1.591	38.	-0.00129	-0.00134	-0.00135	-0.00149
5.00	1.559	46.	-0.00126	-0.00131	-0.00133	-0.00146
6.00	1.548	55.	-0.00124	-0.00130	-0.00131	-0.00144
8.00	1.539	73.	-0.00124	-0.00129	-0.00130	-0.00143
10.00	1.537	91.	-0.00123	-0.00128	-0.00129	-0.00143

PRODAS V3.1   Filename: XM483RHW   29-MAY-89

XM483 1974 VERSION
Projectile Length = 936.244 (mm)
Ogive Length = 440.182 (mm)
Boattail Length =   78.867 (mm)
Band Length =   37.846 (mm)



Stability Results

Rifling Twist	3101.3	(mm/rev)	20.0 (cal ibers/rev)
Muzzle Velocity	305.59	(m/sec)	
Aircraft Velocity	0.00	(m/sec)	
Air Density	.001225	(gram/cm**3)	
Air Temperature	15.0	(Deg C)	
Spin Rate	5912.	(RPM)	
Center of Pressure from Nose	147.645	(mm)	0.954 (cal ibers)
Center of Gravity From Nose	566.151	(mm)	3.660 (cal ibers)
Gyroscopic Stability Factor	1.335		
Dynamic Stability Factor	0.318		

APPENDIX B.

AI-TRAJ XM483 Sample Output

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Define the minimum and maximum limits for the geometry

Current (mm)	Current (cal)		Min (mm)		Max (mm)			Min (cal)		Max (cal)
936.3	6.053	1:	842.7	11:	1029.9	Proj. Length	21:	5.448	31:	6.658
440.2	2.846	2:	396.2	12:	484.3	Nose Length	22:	2.561	32:	3.131
2367.	15.3	3:	2130.	13:	2603.	Nose Radius	23:	13.8	33:	16.8
78.9	0.510	4:	0.0	14:	86.8	Boattail Length	24:	0.000	34:	0.561
0.0	0.000	5:	0.0	15:	77.3	Boom Length	25:	0.000	35:	0.500
157.5	1.018	6:	157.5	16:	157.5	Band Diameter	26:	1.018	36:	1.018
566.2	3.660	7:	509.5	17:	622.8	CG from Nose	27:	3.294	37:	4.026
18.6	0.120	8:	0.0	18:	20.4	Meplat Diameter	28:	0.000	38:	0.132
3094.	20.0	9:	2784.	19:	3403.	Twist (/rev)	29:	18.0	39:	22.0

Key in item number "," value to modify
Key in "DONE" to continue
Key in "LIST" to relist
Key in "PRINT" for a Line printer output

Key in "ABORT" to return to the Main Menu

XM483 : rhw

ID	Gun Dia. (mm)	Twist (cal/rev)	Chamber Volume (cm**3)	Barrel Length (cm)	Proj. Wgt. (kg)	Tube ID	Proj ID	Prop ID
9	155.0	20.0	19123.6	504.4	43.1	M185	M483	M4A2

Zone	Charge (kg)	Velocity (m/s)	Pressure (bars)
3.	1.76	294.9	427.49
4.	2.32	334.7	537.81
5.	3.11	385.9	730.87
6.	4.38	461.5	1041.15
7.	5.96	546.8	1730.64
8.	9.23	648.6	2061.60

A total of 32 Linear Theory 2DOF trajectories will now be run

Run No.	Temp (Deg C)	VZERO (m/sec)	QE (deg)	AZERO (deg)	TOF (sec)	Range (m)	V-Final (m/sec)	A-Final (deg)
1	15.0	294.9	15.0	2.8	15.2	4025.5	258.2	1.8
2	15.0	294.9	15.0	7.0	15.1	3992.6	257.2	1.6
3	15.0	294.9	15.0	10.5	15.1	3705.1	210.9	16.7
4	15.0	294.9	15.0	14.0	14.7	3432.6	199.7	17.1
5	15.0	334.7	15.0	2.8	16.8	4863.4	277.1	0.3
6	15.0	334.7	15.0	7.0	16.7	4810.5	275.2	0.3
7	15.0	334.7	15.0	10.5	16.7	4772.4	274.2	0.3
8	15.0	334.7	15.0	14.0	16.3	4145.2	209.5	16.9
9	15.0	294.9	30.0	2.8	28.8	6559.7	245.4	1.5
10	15.0	294.9	30.0	7.0	28.7	6505.7	244.5	1.4
11	15.0	294.9	30.0	10.5	28.3	5601.7	188.4	16.9
12	15.0	294.9	30.0	14.0	27.0	5063.8	181.5	16.8
13	15.0	334.7	30.0	2.8	31.8	7895.3	264.6	0.8
14	15.0	334.7	30.0	7.0	31.6	7800.1	263.1	0.7
15	15.0	334.7	30.0	10.5	31.5	7724.0	262.0	1.0
16	15.0	334.7	30.0	14.0	29.8	6011.6	191.0	16.7
17	-40.0	294.9	15.0	6.4	15.0	3658.7	203.8	17.2
18	-40.0	294.9	15.0	15.9	13.9	2992.6	181.1	17.2
19	-40.0	294.9	15.0	17.0	13.8	2982.8	181.0	17.2
20	-40.0	294.9	15.0	17.0	13.8	2982.8	181.0	17.2
21	-40.0	334.7	15.0	4.0	16.2	4463.7	259.3	0.4
22	-40.0	334.7	15.0	10.0	16.1	4388.1	256.0	0.4
23	-40.0	334.7	15.0	15.0	16.0	4314.6	254.5	0.5
24	-40.0	334.7	15.0	17.0	15.9	4275.2	253.6	0.5
25	-40.0	294.9	30.0	6.4	28.5	5796.0	188.3	16.8
26	-40.0	294.9	30.0	15.9	25.3	4418.5	167.7	16.8

XM483 : rhw

Run No.	Temp (Deg C)	VZERO (m/sec)	QE (deg)	AZERO (deg)	TOF (sec)	Range (m)	V-Final (m/sec)	A-Final (deg)
27	-40.0	294.9	30.0	17.0	25.2	4367.3	166.1	17.1
28	-40.0	294.9	30.0	17.0	25.2	4367.3	166.1	17.1
29	-40.0	334.7	30.0	4.0	30.7	7269.6	251.2	1.4
30	-40.0	334.7	30.0	10.0	30.4	7141.0	249.4	0.7
31	-40.0	334.7	30.0	15.0	30.1	7013.8	247.5	0.9
32	-40.0	334.7	30.0	17.0	29.9	6900.4	245.6	0.4

XM483 : rhw

The first max yaw and initial yaw rates were computed using simulated in bore angles. The table below shows the in bore and resultant first maximum yaw for Zone 1 at ambient temperature.

First max yaw for Zone 1
Muzzle Velocity (m/sec): 294.9
Temperature (Deg C): 15.0

In Bore Yaw (mils)	First Max Yaw (degrees)
1.00	2.81
2.50	7.01
3.75	10.52
5.00	14.03

Expected Performance at Temperature (Deg C) = 15.0

Gun Elevation (deg)			15.0		30.0	
Velocity (m/sec)	SG(M)	ABAR (deg)	Range (m)	Status	Range (m)	Status
294.9	1.3	2.8	4025.	0	6560.	0
		7.0	3993.	0	6506.	0
		10.5	3705.	8	5602.	8
		14.0	3433.	8	5064.	8
334.7	1.3	2.8	4863.	0	7895.	0
		7.0	4810.	0	7800.	0
		10.5	4772.	1	7724.	0
		14.0	4145.	8	6012.	8

Analysis of trajectories at 15.0 (Deg C)

	Runs	Short	Gyro Short
Number	16	6	6
Percent	100.0	37.5	37.5

Short rounds at muzzle velocities between 294.9 and 334.7 (m/sec) and first max yaws above 10.5 (degrees)
Diagnosis: large positive magnus ; problem = 8
with low muzzle gyro

XM483 : rhw

Expected Performance at Temperature (Deg C) = -40.0

Gun Elevation (deg)			15.0		30.0	
Velocity (m/sec)	SG(M)	ABAR (deg)	Range (m)	Status	Range (m)	Status
294.9	1.0	6.4	3659.	4	5796.	4
		15.9	2993.	8	4418.	8
		17.0	2983.	8	4367.	8
		17.0	2983.	8	4367.	8
334.7	1.1	4.0	4464.	2	7270.	2
		10.0	4388.	2	7141.	2
		15.0	4315.	0	7014.	2
		17.0	4275.	0	6900.	9

Analysis of trajectories at -40.0 (Deg C)

	Runs	Short	Gyro Short
Number	16	7	7
Percent	100.0	43.8	43.8

Short rounds at muzzle velocities between 294.9 and 334.7 (m/sec)
and first max yaws above 15.9 (degrees)
Diagnosis: large positive magnus ; problem = 8
with low muzzle gyro

The initial conditions listed below can be further simulated by 6DOF
(problem areas are coded)

Category	Probable Cause		
0	No problem	1	6DOF info run (no problem)
2	Low terminal gyro	3	Slow arm limit cycle >6
4	Fast arm undamping	5	Slow arm short round
6	Fast arm short round	7	Low muzzle gyro - slow arm short round
8	Low muzzle gyro - fast arm short round	9	Problem ??? short round please run 6DOF
10	Gyro unstable at muzzle		

ID #	Run #	Temp. (Deg C)	Velocity (m/sec)	QE (deg)	ABAR (deg)	ALFDOT (rad/sec)	Problem ID	6DOF Analysis
1	3	15.0	294.9	15.0	10.5	2.21	8	1

Flight Time (seconds)

Attribute	0	5	15	30	50	100
Gyro Unstable	0	0	0	0	0	0
Fast Damping	0	0	0	0	0	0
Fast Limit	0	0	0	0	0	0
Fast Undamping	0	0	0	1	0	0
Slow Damping	0	0	0	1	0	0
Slow Limit	0	0	0	0	0	0
Slow Undamping	0	0	0	0	0	0
Short Fast	0	0	0	0	0	0
Short Slow	0	0	0	0	0	0
Increase Gyro	0	0	0	0	0	0
Short ????	0	0	0	0	0	0

ID #	Run #	Temp. (Deg C)	Velocity (m/sec)	QE (deg)	ABAR (deg)	ALFDOT (rad/sec)	Problem ID	6DOF Analysis
2	11	15.0	294.9	30.0	10.5	2.21	8	1

Flight Time (seconds)

Attribute	0	5	15	30	50	100
Gyro Unstable	0	0	0	0	0	0
Fast Damping	0	0	0	0	0	0
Fast Limit	0	0	0	0	0	0
Fast Undamping	0	0	0	1	0	0
Slow Damping	0	0	0	1	0	0
Slow Limit	0	0	0	0	0	0
Slow Undamping	0	0	0	0	0	0
Short Fast	0	0	0	0	0	0
Short Slow	0	0	0	0	0	0
Increase Gyro	0	0	0	0	0	0
Short ????	0	0	0	0	0	0

XM483 : rhw

ID #	Run #	Temp. (Deg C)	Velocity (m/sec)	QE (deg)	ABAR (deg)	ALFDOT (rad/sec)	Problem ID	6DOF Analysis
3	4	15.0	294.9	15.0	14.0	2.94	8	1

Attribute	Flight Time (seconds) 0	5	15	30	50	100
Gyro Unstable	0	0	0	0	0	0
Fast Damping	0	0	0	0	0	0
Fast Limit	0	0	0	0	0	0
Fast Undamping	0	0	1	0	0	0
Slow Damping	0	0	1	0	0	0
Slow Limit	0	0	0	0	0	0
Slow Undamping	0	0	0	0	0	0
Short Fast	0	0	0	0	0	0
Short Slow	0	0	0	0	0	0
Increase Gyro	0	0	0	0	0	0
Short ????	0	0	0	0	0	0

ID #	Run #	Temp (Deg C)	V-ZERO (m/sec)	QE (deg)	A-ZERO (deg)	TOF (sec)	Range (m)	V-Final (m/sec)	A-Final (deg)
1	3	15.0	294.9	15.0	10.5	15.2	3780.5	216.2	17.7
2	11	15.0	294.9	30.0	10.5	28.7	5924.8	196.3	18.5
3	4	15.0	294.9	15.0	14.0	15.0	3569.6	203.6	17.6

The conditions listed below have been further investigated
by 6DOF simulations and the results are tabulated below

ID #	Run #	Temp. (Deg-C)	MV (m/sec)	QE (deg)	ABAR (deg)	ALFDOT (rad/sec)	Problem ID	Range 2D (m)	Range 6D (m)	Range Ref (m)
1	3	15.0	294.9	15.0	10.5	2.2	8	3705.1	3780.5	4025.5
2	11	15.0	294.9	30.0	10.5	2.2	8	5601.7	5924.8	6559.7
3	4	15.0	294.9	15.0	14.0	2.9	8	3432.6	3569.6	4025.5

XM483 : rhw

Case No.	Temp (Deg C)	Vel (m/sec)	QE (deg)	ABAR (deg)	ADOT (rad/sec)
3	15.0	294.9	15.0	10.52	2.21

Range (2DOF) (ft)	Range (6DOF) (ft)	Range (no yaw) (ft)	% of expected range
3705.1	3780.5	4025.5	93.91

Time (sec)	Vel (m/sec)	KF (deg)	KS (deg)	LF (1/m)	LS (1/m)	WF (deg/m)	WS (deg/m)	Repose (deg)	SIGFIT (deg)
0.0	294.8	5.3	5.2	0.00035	-0.00220	7.19	2.40	-0.20	0.11
0.5	291.1	5.7	3.7	0.00025	-0.00212	7.35	2.32	-0.22	0.09
1.0	287.6	5.9	2.7	0.00024	-0.00210	7.50	2.26	-0.23	0.08
1.5	284.4	6.1	2.0	0.00027	-0.00214	7.63	2.20	-0.24	0.07
2.0	281.3	6.3	1.5	0.00030	-0.00210	7.76	2.16	-0.25	0.06
2.5	278.5	6.6	1.1	0.00034	-0.00202	7.87	2.08	-0.26	0.06
3.0	275.7	6.9	0.8	0.00038	-0.00191	7.98	1.96	-0.27	0.06
3.5	273.1	7.2	0.6	0.00042	-0.00195	8.10	2.00	-0.28	0.06
4.0	270.5	7.6	0.5	0.00046	-0.00216	8.20	2.09	-0.28	0.05
4.5	268.0	8.1	0.3	0.00050	0.00000	8.29	1.88	-0.29	0.06
5.5	263.0	9.2	0.2	0.00060	0.00000	8.49	1.82	-0.31	0.05
6.5	258.1	10.8	0.1	0.00052	0.00000	8.72	1.72	-0.34	0.04
7.5	252.9	12.3	0.1	0.00043	0.00000	8.97	1.62	-0.36	0.06
8.4	247.6	13.6	0.1	0.00034	0.00000	9.23	1.52	-0.39	0.13
9.4	242.4	14.8	0.1	0.00026	0.00000	9.49	1.40	-0.41	0.23
10.4	237.2	15.7	0.0	0.00021	0.00000	9.76	1.29	-0.44	0.25
11.4	232.2	16.4	0.0	0.00015	0.00000	10.02	1.22	-0.48	0.34
12.4	227.5	17.1	0.0	0.00012	0.00000	10.25	1.14	-0.50	0.44
13.3	223.2	17.5	0.0	0.00009	0.00000	10.44	1.05	-0.51	0.54

XM483 : rhw

Attribute	Flight Time (seconds) 0	5	15	30	50	100
Gyro Unstable	0	0	0	0	0	0
Fast Damping	0	0	0	0	0	0
Fast Limit	0	1	1	0	0	0
Fast Undamp	1	0	0	0	0	0
Slow Damping	1	1	1	0	0	0
Slow Limit	0	0	0	0	0	0
Slow Undamp	0	0	0	0	0	0
Short Fast	0	1	1	0	0	0
Short Slow	0	0	0	0	0	0
Increase Gyro	1	1	0	0	0	0

	2DOF	6DOF
Problem Code	8	8
Percent Short	92.04	93.91

XM483 : rhw

Case No.	Temp (Deg C)	Vel (m/sec)	QE (deg)	ABAR (deg)	ADOT (rad/sec)
11	15.0	294.9	30.0	10.52	2.21

Range (2DOF) (ft)	Range (6DOF) (ft)	Range (no yaw) (ft)	% of expected range
5601.7	5924.8	6559.7	90.32

Time (sec)	Vel (m/sec)	KF (deg)	KS (deg)	LF (1/m)	LS (1/m)	WF (deg/m)	WS (deg/m)	Repose (deg)	SIGFIT (deg)
0.0	294.8	5.4	5.1	0.00021	-0.00210	7.19	2.39	-0.19	0.24
0.5	289.8	5.6	3.6	0.00014	-0.00202	7.43	2.29	-0.20	0.21
1.0	285.3	5.7	2.7	0.00016	-0.00216	7.65	2.22	-0.22	0.19
1.5	281.0	5.8	2.0	0.00018	-0.00211	7.86	2.17	-0.22	0.16
2.0	277.0	5.9	1.5	0.00022	-0.00182	8.03	1.98	-0.25	0.15
2.5	273.2	6.1	1.2	0.00023	-0.00181	8.19	1.71	-0.25	0.15
3.0	269.5	6.3	0.9	0.00025	-0.00143	8.38	2.20	-0.30	0.15
3.5	265.9	6.5	0.8	0.00024	-0.00205	8.53	1.77	-0.31	0.15
4.0	262.5	6.8	0.6	0.00019	-0.00267	8.67	1.17	-0.26	0.15
4.4	259.1	7.0	0.4	0.00018	0.00018	8.83	2.57	-0.28	0.14

XM483 : rhw

Attribute	Flight Time (seconds) 0	5	15	30	50	100
Gyro Unstable	0	0	0	0	0	0
Fast Damping	0	0	0	0	0	0
Fast Limit	0	1	0	0	0	0
Fast Undamp	1	0	0	0	0	0
Slow Damping	1	1	0	0	0	0
Slow Limit	0	0	0	0	0	0
Slow Undamp	0	0	0	0	0	0
Short Fast	0	1	0	0	0	0
Short Slow	0	0	0	0	0	0
Increase Gyro	1	0	0	0	0	0

	2DOF	6DOF
Problem Code	8	8
Percent Short	85.40	90.32

XM48.

Case No.	Temp (Deg C)	Vel (m/sec)	QE (deg)	ABAR (deg)	ADOT (rad/sec)
4	15.0	294.9	15.0	14.03	2.94

Range (2DOF) (ft)	Range (6DOF) (ft)	Range (no yaw) (ft)	% of expected range
3432.6	3569.6	4025.5	88.68

Time (sec)	Vel (m/sec)	KF (deg)	KS (deg)	LF (1/m)	LS (1/m)	WF (deg/m)	WS (deg/m)	Repose (deg)	SIGFIT (deg)
0.0	294.8	7.0	6.8	0.00049	-0.00228	7.25	2.38	-0.21	0.20
0.5	290.5	7.5	4.8	0.00051	-0.00232	7.44	2.29	-0.23	0.18
1.0	286.5	8.1	3.4	0.00054	-0.00245	7.62	2.22	-0.24	0.17
1.5	282.7	8.7	2.4	0.00058	-0.00247	7.80	2.18	-0.25	0.15
2.0	279.1	9.5	1.8	0.00060	-0.00208	7.97	2.11	-0.24	0.16
2.5	275.5	10.3	1.3	0.00058	-0.00156	8.14	1.77	-0.29	0.17
3.0	272.0	11.2	1.0	0.00053	-0.00145	8.33	2.09	-0.32	0.18
3.5	268.4	12.1	0.8	0.00047	-0.00087	8.51	2.18	-0.27	0.17
4.0	264.7	12.9	0.8	0.00040	-0.00187	8.68	1.31	-0.33	0.16
4.5	261.1	13.6	0.5	0.00036	-0.00015	8.87	2.24	-0.37	0.15

```
XM483    : rhw


Projectile analysis history

Analysis number            :         1
Failure code               :         8
Percent short trajectories :        43.8

CG from nose     (calibers):       3.660
Twist             (cal/rev):        20.0
Boat tail length (calibers):       0.510
Axial inertia   (lbm-in**2):   0.510E+03
Trans. inertia  (lbm-in**2):   0.610E+04

Low muzzle gyroscopic stability (fast arm)


Recommended projectile modifications
Modifications are listed in order of preference


       Increase rifling twist:
             Current twist is   20.00 (calibers/rev)
             Maximum twist is   22.00 (calibers/rev)


       Modify projectile mass properties
             Move center of gravity forward
             Increase axial inertia
             Decrease transverse inertia
```

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APPENDIX C.

AERO-AI Rule Additions

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Extending AERO-AI - Rule Additions

This Appendix describes the process to extend AERO-AI by changing or adding rules to correct/enhance system performance. First and foremost, it is strongly recommended that initially no changes be made directly to the facts and rules files developed by GE-ATL. It's better to create two new files (perhaps "custom-facts.art" and "custom-rules.art") which can be loaded into ART along with the basic AERO-AI package.

You will need to learn ART to some extent before making any changes. As mentioned above, the "ART Programming Tutorial" series is excellent for novice users. Inference also offers a number of one-week training courses for new users. It's also useful to become familiar with Common LISP and programming in symbolic languages.

The basic procedure for extending AERO-AI is as follows:

1. Write the new rules.

   It is very important that new rules be placed into their proper partition in the Domain Subsection. The following guidelines should be used.

   - GENERATE - Creates class I recommendations and info-messages. These rules should be rather simple in nature, and should NOT look at the projectile's design history or its geometry restrictions. They should consider only the geometry metrics and AITRAJ analysis.
   - REFINE - The projectile's design history should be considered in this partition, as well as any other data OTHER THAN GEOMETRY RESTRICTIONS which might cause a recommendation to change. Class I recommendations may be deleted, altered, or translated verbatim into Class II recommendations. In addition, new Class II recommendations may be created from scratch.
   - REVIEW - Class II recommendations are compared against the geometry restrictions specified by the user. If a recommendation violates any restriction, it should be designated Class R. (Specify the class as "(R (GEO (metric)))", where (metric) is the geometry value that prevents the recommendation from being made.) Otherwise, designate it Class F. Review is very much a closed partition. The rules which check for geometry restrictions have been written and tested for recommendations of up to arity 2. These rules use the GEOMETRY-METRIC facts in the Initial Factbase, so this is where virtually all alterations should be made.

   It is strongly advised that you adhere to this functional division of the rulebase. Yes, it is often possible to combine rules from different partitions into one efficient but complex rule. However, the small amount of execution time this saves is not nearly worth the increased complexity of the rulebase and the associated difficulty in maintaining the code.

   You should use a rule-naming scheme similar to the one used in the GE rulebase file. Saliences should be specified using the 10 global variables ("?*IO*", "?*PT3*", etc.) defined in the facts file.

2. Develop new auxiliary code (usually in parallel with step 1).

As stated earlier, it is a good idea to do as much algorithmic work as possible using the Callout facility. Write your LISP (or C) code in parallel with your new rules. Volumes 1 and 3 of the ART Programming Tutorial series have sections on proper use of the Callout facility.

In the Vax/C version of AERO-AI, auxiliary functions must be linked to the basic ART kernel to create a new executable file. Complete instructions can be found in the Appendices of the ART Reference Manual.

3. Update the facts file

   First, define any new relation names which you used in your custom rules. ART's DEFRELATION statement is the relevant construct. It's useful to include the "SYNTAX" argument to document your new relation.

   You should virtually NEVER make any changes to the global variables section unless you are very sure what you're doing. They control the flow of execution among partitions.

   If you created a new RecCode, you may need to make some modifications to the Initial Factbase. The most important one will be to add new GEOMETRY-METRIC facts if your new recommendation will cause a change in the projectile's geometry. Note that some recommendations affect more than one metric. For example, decreasing the boattail length (VB) will also decrease the total length of the projectile (VL), therefore two GEOMETRY-METRIC facts are needed.

   The other three types of facts will rarely require updating. ASP-ZONING should remain unaltered unless the programmer specifically wants to change how AERO-AI handles Zoning problems. THRESHOLD will only change if a new geometry metric is added to PRODAS, something that will be exceedingly rare. Finally, new VB-OSCILLATION facts may be necessary only if your new recommendation might become part of a boattail oscillation (i.e., it specifically recommends that the user change the projectile's boattail length.) See section 2.3 for the interpretation of the VB-OSCILLATION relation.

4. Update the RecCodes file.

   If you defined a new RecCode or InfoCode, you will have to declare it in the RecCode Definition file. See section 2.2 for the syntax of the declarations. Remember to write messages of arity 1 or higher as Common LISP FORMAT templates. The order of the declarations is not important.

5. Update the AERO-AI initialization file

   Finally, you must ensure that your new facts and rules will be loaded into ART when a user invokes AERO-AI. There are a number of ways to accomplish this, so the actual method used will be left to the system manager. One feasible approach is outlined below.

   You may elect to completely recompile the AERO-AI rule base so that the save file ("aeroai-rules.lbin" contains both GE's initial rulebase and your custom rules. This is done by entering ART and loading all necessary files (both GE's and yours). You should load auxiliary code files first, facts files second, and rules files last. Obviously, if ART notifies you of any syntax errors you will have to make the necessary corrections and start over. After everything is loaded, reset the expert system and run the SAVE utility to create a new "aeroai-rules.lbin" file. This will automatically be restored when AERO-AI is invoked.

An alternate approach for updating the AERO-AI initialization file file,

(aeroai$home:aeroai)

so that your custom rules and facts are loaded after the compiled rulebase is restored, entails putting a few "ART-LOAD" statements between the "RESTORE" and the "RESET" commands.

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